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EDDY DIFFUSION AND BACTERIAL REDUCTION IN WASTE FIELDS IN THE OCEAN

James E. Foxworthy, et al

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Los Angeles, California

September 1969

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EDDY DIFFUSION AND BACTERIAL REDUCTION IN WASTE FIELDS IN THE OCEAN

JAMES E. FOXWORTHY
HERMAN R. KNEELING

REPORT 69-1

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FINAL REPORT

EDDY DIFFUSION AND BACTERIAL REDUCTION IN WASTE FIELDS IN THE OCEAN

RESEARCH GRANT WP 00931

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

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THE ALLAN HANCOCK FOUNDATION

Details of illustrations in
this document may be better
studied on microfiche.

UNIVERSITY OF SOUTHERN CALIFORNIA
LOS ANGELES, CALIFORNIA
SEPTEMBER 1969

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*Presently, Dean of the College of Engineering
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Introduction - Objectives

The material presented in this report is an extension of previous studies of turbulent eddy diffusion in the ocean conducted by the Allan Hancock Foundation. The work began in 1962 and continued under a series of U.S. Public Health Service Demonstration Grants through 1965. The results of these studies were presented in terms of multi-dimensional models of turbulent diffusion of a conservative tracer dye emitted from point and large-scale sources. A detailed amount of the results of this work was presented in a series of technical publications referred to later in this report.

During the course of these investigations several important questions were raised which ultimately formed the basis or objectives of the present research. These objectives were:

1. to extend the previously proposed models of turbulent diffusion from continuous point and large-scale sources by formulating a term to account for the rate of change of non-conservative substances, e.g., indicator bacteria.
2. to investigate the validity of the basic assumption of a normal or Gaussian distribution of waste constituent concentration inherent in the proposed diffusion models.
3. to gather additional information on the surface dispersion characteristics of waste material discharged from submarine outfalls equipped with and without diffuser systems. This information is to be used to assess the effects of initial size of a surface waste field on the rate of subsequent dilution of waste waters.

4. to assess the effects of various environmental factors, e.g., seasonal variation, water temperature, gross solar radiation, sedimentation, etc. on the observed rates of disappearance of indicator bacteria.

Preliminary Studies

Selection of a Non-Conservative Waste Constituent

The term non-conservative as used herein applies to any constituent of waste water that undergoes changes in concentration other than that brought about by the physical processes of dilution and sedimentation. One particular non-conservative constituent of waste waters that has been used for many years to indicate the presence of pollution is the coliform group of bacteria. Several methods have been developed for the reliable and relatively rapid detection and enumeration of coliforms in fresh and salt water. Consequently, this bacteriological group was selected as the primary non-conservative waste constituent to be studied in these investigations.

Recently considerable attention has been given to the potential value of the fecal streptoccal group of bacteria as a more definitive indicator of pollution in the ocean. In a recent laboratory investigation, Hanes and Fragala (1967) reported that the growth phase and subsequent death rate of coliform organisms in waste-sea water mixtures was dependent on the concentration of sea water. They found that for mixtures containing 67 percent or more sea water the growth phase disappeared completely. Increased sea water concentrations were also found to result in increased death rates.

On the other hand it was found that the fecal streptoccal group (referred to as the enterococcal group by the authors) exhibited no growth phase regardless of the concentration of sea water and that the death rate for fecal streptococci was little affected by sea water concentration. These results led Hanes and Fragala to conclude that the fecal streptoccal group of bacteria may be the best indicator of recent enteric pollution in sea water.

Although reliable methods have recently been developed for the enumeration of fecal streptococci, the required incubation time is approximately twice as long (48 hours compared to 18-20 hours for coliforms). In the present studies it was considered necessary, for statistical reasons as discussed later, to process as many bacteriological samples as possible in a limited period of time. This requirement precluded the use of the fecal streptococcal group of bacteria as the primary indicator of non-conservatism. However, in light of the work of Hanes and Fragala a limited series of experiments were conducted in which both indicators were used to investigate the relative differences in the non-conservative properties of these two bacteriological groups.

Effect of Dye Concentration on Coliform Mortality

In our previous large-scale diffusion studies the entire flow from a selected waste treatment plant was tagged with tracer dye before discharge to the ocean. The dye, 40% rhodamine B in acetic acid solution, was injected in sufficient quantity to produce a visible surface plume for a distance of several thousand feet from the point of origin (see Figure 1). It was essential that a well

Oxnard Outfall
October 13, 1966

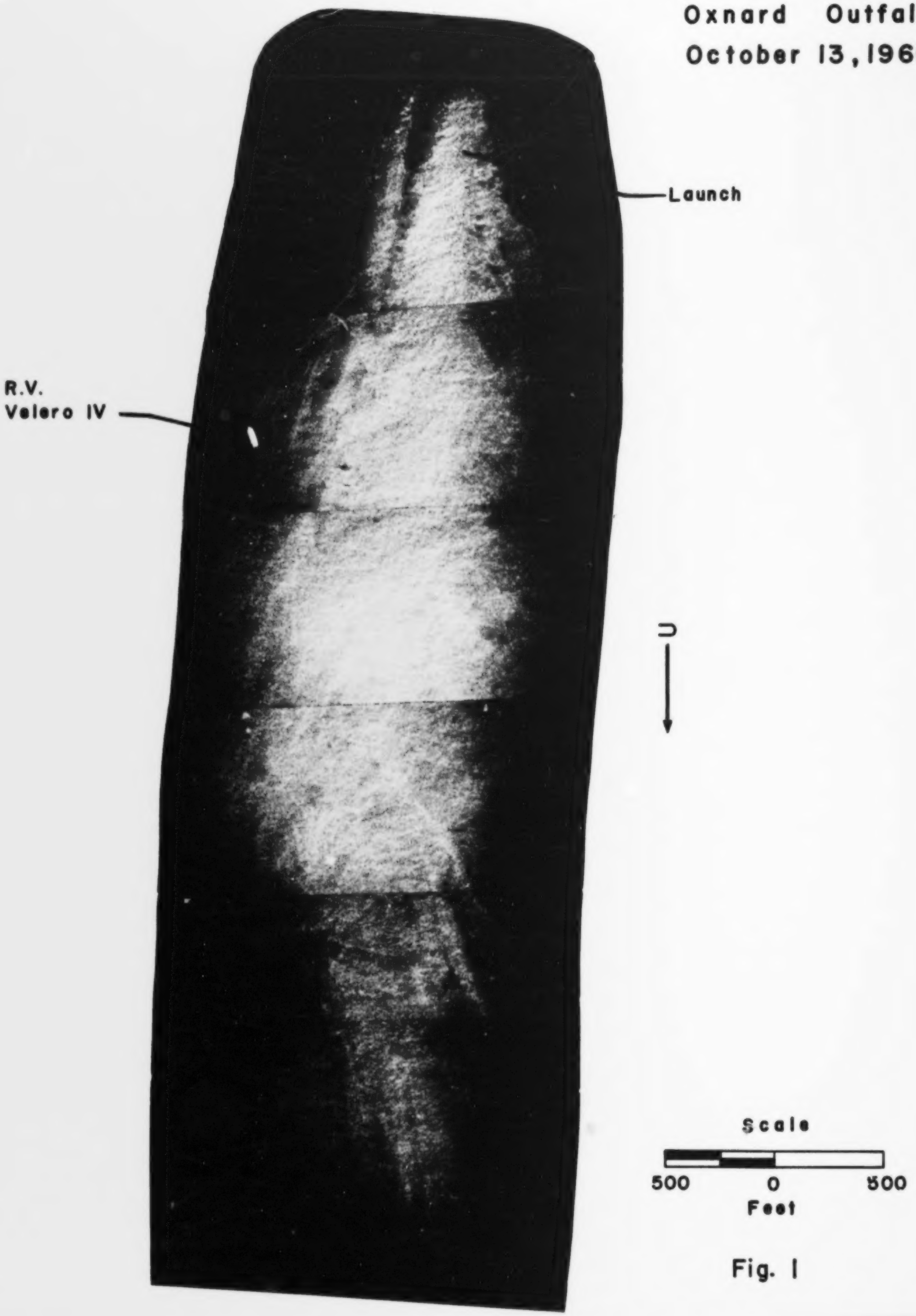

Launch
R.V.
Velero IV
N
Scale
500
0
500
Feet

Fig. 1

delineated waste plume be developed in order to insure accuracy of field sampling techniques and the production of good quality aerial photographs used in the analysis of horizontal diffusion phenomenon. In previous studies the necessary dye concentration in the treatment plant effluent was found to range from 1 to 4 mg/l. The subsequent waste residence time in the submarine outfalls studied ranged from 1 to 3 hours. The observed initial dilution, that is, dilution of the waste between the point of submarine discharge and the water surface ranged from 40/1 to 100/1 (sea water/waste water). As a result, the dye concentration at the origin of the surface plumes ranged from 10 to 100 parts per billion (ppb). Since the same experimental procedure was to be used in the present studies involving indicator bacteria, a series of preliminary laboratory experiments were conducted to assess any possible bactericidal effect of the tracer dye.

Laboratory Procedure. Fresh unchlorinated waste water used in these studies was obtained from the discharge line from the city of Los Angeles Hyperion treatment plant located at Playa Del Rey, California. Approximately two-thirds of the waste flow through the plant receives primary treatment and the remainder secondary treatment before the entire flow is mixed and discharged to the Pacific Ocean.

The laboratory procedure followed in these experiments was as follows:

1. Stock solutions of known dye concentration were prepared by dilution of raw 40% rhodamine B acetic acid solution with distilled water.

2. Five 1000 ml samples of waste effluent were placed in sterile 2000 ml Erlenmeyer flasks. Rhodamine B dye solution was added to four of the flasks to produce concentrations of 1, 2, 3, and 4 mg/l respectively. The flask without dye was used as a control. The contents of each flask were mixed for 5 minutes after which samples were withdrawn for initial bacteriological analysis as discussed below. The flasks were then stored in the dark at room temperature. Additional samples for bacteriological analysis were withdrawn from the flasks at 1, 2, 3, and 4 hour intervals.
3. Coliform densities were determined by the membrane filter technique as described in Standard Methods (1965). A one ml sample from a given flask was mixed with buffered dilution water to produce a final dilution of 10^4 (dilution water/waste). Several replicate samples of the diluted waste were filtered through type HA millipore filters and the innoculated filters incubated in pre-sterilized disposable plastic petri dishes. The medium used was M-Coliform Broth (B.B.L.). All plates were incubated for 18-20 hours at 35 ± 2° C. before counting.

Experimental Results. A series of independent experiments were conducted in which four replicate samples were analyzed for each dye concentration at each of the 0 to 4 hour time intervals. Mean coliform densities were computed for each dye concentration at a given elapsed time after start of the experiment. The results are shown graphically in Figure 2. It is difficult to establish

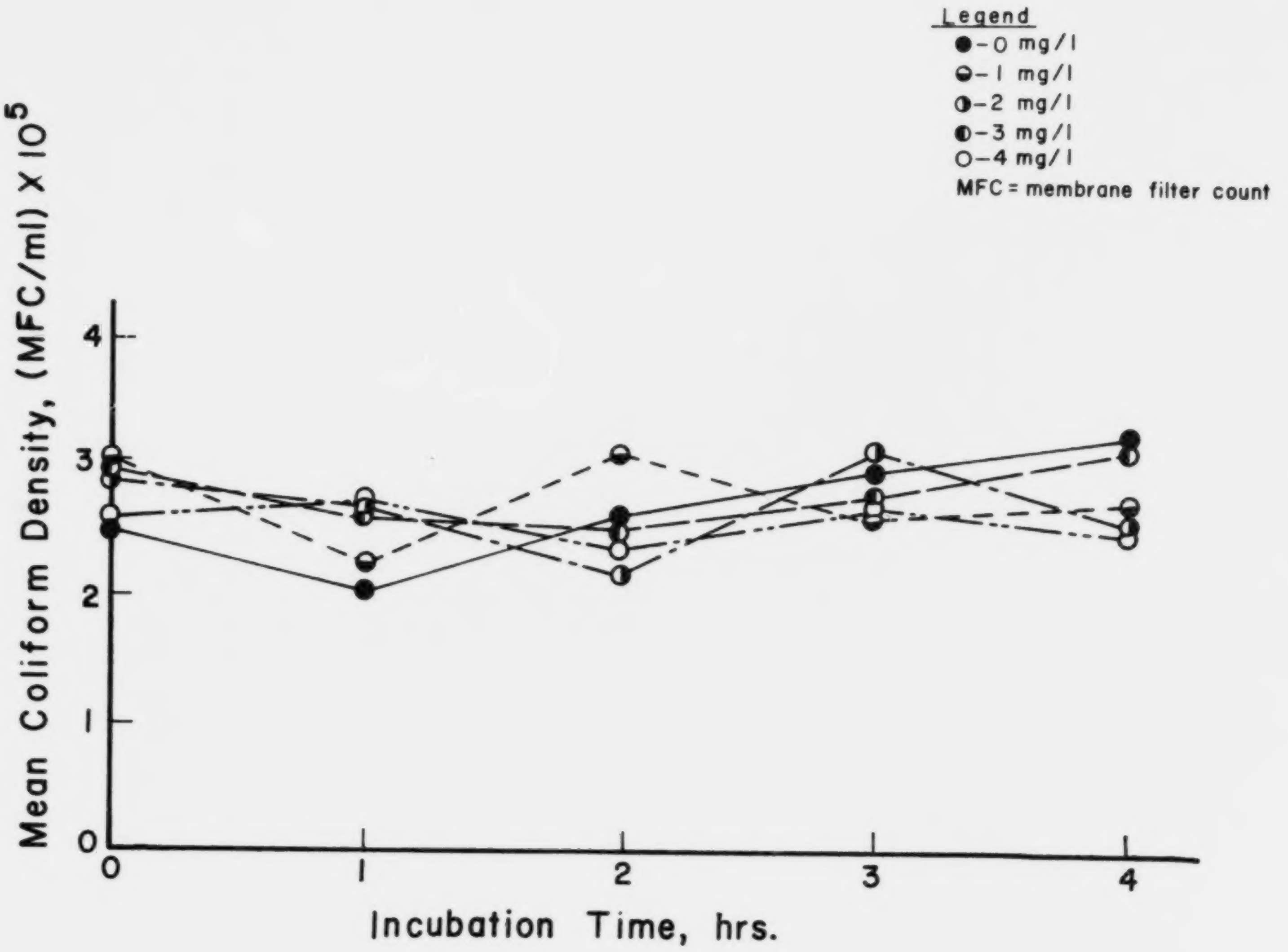

Legend
●-0 mg/l
⊖-1 mg/l
◑-2 mg/l
◐-3 mg/l
○-4 mg/l
MFC = membrane filter count
Mean Coliform Density, (MFC/ml) X 10^5
0
1
2
3
4
0
1
2
3
4
Incubation Time, hrs.

Fig. 2

any visible trend for these data except to note that at the start of the test the mean coliform density of the control samples was less than that of the samples containing dye, while four hours later the situation was reversed. This result could be taken as an indication that the dye resulted in an inhibition of the growth chatacteristic observed in the control samples. However, before any firm conclusions could be made, it was first necessary to determine if the observed differences in mean coliform densities at any time were due to chance only or actually due to the presence of the dye. In this case student's t-test for the comparison of means was applied to the data to test the null hypothesis that there is no significant difference between the mean value of the control sample and any of the dyed samples. An example of the results of this analysis for the mean values obtained at the 0 and 4 hour incubation times are shown in Table 1. In each case the computed value of the t-variable from the experimental data is considerably less than the critical value, $|t_0|$, at the 1% level of significance. Therefore it is highly probable that there was no significant difference between the mean values of the coliform densities from the control and dyed waste samples at the 0 and 4 hour incubation times, i.e., we accept the null hypothesis. Similar results were obtained for the data obtained at other incubation times. From these results it was concluded that rhodamine B dye has little or no bactericidal effect on coliforms for the dye concentrations and incubation times discussed above.

On the basis of these results it was also concluded that the maximum dye concentrations previously observed in the surface plumes

Table 1

Significance Tests

Time of Incubation	Dye Concentration mg/l	$\lvert t \rvert$	$\lvert t_0 \rvert$ 1% Significance Level	ν
0	1	1.216	4.604	4
"	2	0.315	5.841	3
"	3	1.481	4.604	4
"	0	0.106	4.604	4
4	1	0.862	5.841	3
"	2	0.931	5.841	3
"	3	0.398	5.841	3
"	4	0.928	5.841	3

$\lvert t \rvert$ = Calculated value of t-variable between mean values of coliform concentration for control samples and samples with indicated dye concentrations.

$\lvert t_0 \rvert$ = Critical value of t-variable at 1% significance level.

ν = Number of degrees of freedom.

Reference: Adam M. Melville and John B. Kennedy, "Basic Statistical Methods for Scientists and Engineers." International Textbook Co. (1964)

(10 to 100 p.p.b.) over the terminus of the outfalls studied would have little or no effect on the survival of indicator bacteria.

Factors Affecting Bacterial Disappearance

Aside from the possible effect of externally applied tracers, several environmental factors are thought to influence the disappearance of enteric bacteria in sea water. Pramer, et al (1936), Waksman and Hotchkiss (1937), Pearson (1956), Greenberg (1957), and Carlucci and Pramer (1959) are among the authors who have presented extensive reviews of previous laboratory and field studies of this phenomenon. In general these authors agree that the most significant destructive agent(s) in sea water may be biological in nature, heat labile, and related to the normal population of organisms indigenous to a particular oceanic area.

Carlucci and Pramer (1959) summarized some of the relevant factors or agents in sea water which may contribute to the disappearance of enteric bacteria. Among those are: (1) adsorption and sedimentation; (2) the destructive action of sunlight; (3) the lack of required nutrients; (4) the presence in sea water of toxic substances; (5) the presence of bacteriophages; (6) the utilization of bacteria as food by protozoa and other predators; and (7) the competative and antagonistic effects of other microorganisms. In addition to the above factors Mitchell and Morris (1968) stressed the fact that the bactericidal action in sea water varies greatly with the season of the year as well as the source of the sample. They refer to the results of laboratory studies conducted by Vaccaro, et al (1950) which showed that the time necessary to produce

90% reduction of E. Coli added to Vineyard Sound water varied by an order of magnitude (14 hr to 140 hrs.) for water collected in July compared to that collected in November. On the other hand, field studies conducted by Thomas (1964) on the disappearance of coliform in waste water discharged into Titahi Bay, New Zealand gave a time for 90% reduction of only 40 minutes. Similar results have been obtained by other investigators as will be discussed later in this report.

Recent Laboratory Findings. Several recent attempts have been made to determine through laboratory experiments, the relative importance of environmental factors such as those listed above on coliform disappearance in the marine environment. The results of some of this work have direct bearing on the findings presented herein and will be discussed briefly at this time. The work of Hanes and Fragala (1967) on the effect of the concentration of sea water on the growth and subsequent death of coliform, and fecal streptococcal bacteria was referred to previously. In short these authors found that the tendency of coliform organisms to grow in sea water was suppressed when sea water concentrations were greater than about 67% by volume. No tendency for growth of fecal streptocci was observed even with sea water concentrations as low as 33%. The death rates of both bacterial groups increased with increasing sea water concentrations.

Mitchell and Morris (1968) conducted a series of experiments designed to evaluate the effects of native marine microbial concentrations on the death of intestinal bacteria in the sea. They found that the rate of kill increased with increase in native microbial population.

At least two groups of bacteria were found by these authors to be associated with the death of E. Coli in sea water. One group, Pseudomonas, was found to predominate in samples of sea water following the repeated addition of E. Coli both in artificial and heat sterilized sea water.

Another group of relatively common marine bacteria, Bdellvibrio, were also found to kill E. Coli. Their studies showed that this organism is an obligate parasite which will not grow on E. Coli unless the host bacterium is placed in sea water.

An additional important finding of these experiments was that nematodes, commonly found in sea and other waters-- especially in polluted areas-- contribute to the kill of E. Coli., but at a slower rate than bacteria. Mitchell and Morris also presented data to support their hypothesis that an antagonistic microbial population develops in response to the addition of intestinal bacteria to sea water. Their experiments showed that although no dramatic increase in total microbial population occurred concurrently with the destruction of E. Coli, a shift in population toward specifically antagonistic microbial groups probably took place.

In summarizing the results of their experiments these authors stressed that the relative and absolute importance of each of the above groups of organisms in killing E. Coli will vary temporally and geographically, depending on the particular ecological situation.

The results of an interesting series of laboratory experiments designed to evaluate the possible antibacterial action of marine plankton on enteric and other bacteria was reported by Aubert, et al (1968). According to these authors extracts from marine plankton when added to heat sterilized sea water restored its antibiotic action. Using bioassay methods it was found that extracts from several Diatoms and Dinoflagellates have apparent antibiotic activity towards various enteric bacteria, including *E. Coli.* These authors further report that antibiotic substances originating from plankton, when released into the marine environment, are capable of producing an antibiotic effect, and their combined action ensures its continual presence. Aubert, et al, also point out that other investigators have shown the presence of antibacterial substances of a marine origin in such organisms as: molluscs, corals, Spongiae, brown, red, or green algae, and, also, in marine algae, It should be mentioned, however, that the ecological significance of antibacterial extracts obtained from marine organisms has been questioned by Brisou (1968). He contended that since these extracts can only be released by physical disintegration or by lysis, their significance in reducing the numbers of certain marine bacteria may be minimal.

Recent Field Experience. From the above discussion it appears that many individual and probably interrelated factors are involved in promoting bacterial reduction in the ocean. Under such conditions it is difficult, if not impossible, to conduct relevant laboratory experiments designed to show the overall effects of these factors. It is for these and other reasons that investigators have turned their attention to conducting experiments under full field conditions.

Much of our present knowledge of this subject originated from a series of field experiments sponsored by Hyperion Engineers, Inc. (1957). These studies were conducted in the vicinity of three submarine outfalls located off the coast of southern California. Slugs of Fluorescein dye were released within the surface waste fields formed over these outfalls. The tagged water mass was followed for several hours and grab samples for subsequent chemical and bacteriological analyses were taken from the water surface and at various depths. Coliform densities were determined by standard fermentation tube methods and physical dilution of the waste was estimated from salinity measurements, and in one case, by use of a radioactive tracer. From these data it was possible to separate the components of physical dilution and coliform reduction. The results of these experiments were reported in terms of the time (in hours) required for the coliform concentration to be reduced by ninety percent, expressed by the symbol T_{90}. It was assumed that the temporal distribution of coliform concentration followed Chick's Law (1908), that is,

$$^{C}/C_{0}\ (\%) = {}^{100}/10^{KT} \qquad (1)$$

Where C is the coliform concentration at any drift time T, C_0 is the concentration at the origin of the field, and K is the disappearance rate constant. It can be shown from equation (1) that T_{90} is related to the rate constant by the simple equation

$$T_{90} = {}^{1}/K \qquad (2)$$

Values of T_{90} reported by these authors varied widely and ranged from 1.5 to 6.5 hours. The variation was attributed mainly to adsorption and subsequent sedimentation of coliforms on suspended sewage solids. It was concluded that high suspended solids and concentrations associated with wastes receiving only primary treatment (screening and settling) result in lower T_{90} values.

Similar in situ experiments conducted by da Silva (1963) off the coast of Brazil, resulted in T_{90} values of less than one hour for raw or untreated waste discharged to the ocean.

Engineering Science, Inc. (1965) presented the results of coliform die-away studies conducted off the coast of Ghana. In these experiments untreated waste effluent was continuously tagged with a fluorescent dye (rhodamine B) before discharge to the ocean. The resulting tagged waste field was followed and grab samples were taken near the water surface at regular intervals. These samples were stored for later analysis of dye and coliform concentrations. Dye concentrations were measured by use of a fluouometer and coliform densities were determined by standard membrane filter techniques. The results of these investigations showed that the average T_{90} time for this particular waste was 80 minutes. Since no information was gathered on possible sedimentation effects, the reported T_{90} value is assumed to apply to the overall disappearance of coliforms.

Harremoes (1967,68) conducted experiments on bacterial decay in waste fields dispersing off the coast of Denmark. He found that the rate of disappearance (corrected for dilution) ranged from T_{90} = 66 minutes for the discharge of raw untreated sewage to about T_{90} = 1800 minutes for sewage receiving secondary treatment.

He attributed the difference in disappearance rates to sedimentation of E. Coli on sewage solids.

A different experimental approach was used by Gameson and Saxon (1968) in their attempt to establish the effects of daylight on the die-away of coliform bacterial. These investigators suspended light and dark bottles containing sewage-- sea water mixtures at various depths in the vicinity of a sewage outfall. Periodic determination of the concentration of coliforms in both light and dark bottles made it possible to estimate the rates of die-away as a function of depth and the total amount of radiation received by each sample. As in other field experiments it was assumed by these authors that Chick's Law was valid and the results of these studies were expressed in terms of T_{90} values. It was found that high rates of coliform mortality resulted when samples were exposed to sunlight. The total amount of solar radiation required to produce 90% mortality was found to increase with advancing season (May to September) and with increasing depth of immersion. No explanation was given by these authors for the decrease in mortality of coliform organisms exposed to sunlight later in the season (summer months). They point out, however, that the same phenomenon was observed for samples kept in the dark. The variations with depth were attributed to possible light attenuation effects.

Aside from the reference to the effects of sedimentation and sunlight, the above experiments yielded insufficient data to determine the influence of other environmental factors on the observed rates of bacterial reduction. Furthermore, in most of these studies the data were too few to actually verify the applicability of Chick's Law to the disappearance of indicator bacteria in the ocean. This fact is important since many of the commonly employed models of oceanic diffusion incorporate a decay or disappearance term identical or similar to Chick's equation.

In the experiments discussed in this report an attempt was made to obtain sufficient data to establish a rigorous mathematical formulation for coliform disappearance in the ocean. In addition an attempt was made to investigate the influence of several of the environmental factors discussed previously on the observed rates of coliform reduction.

Field Experiments

Outfall Characteristics

To fulfill the objectives of this research it was first necessary to select representative submarine outfall systems for subsequent study. The outfalls operated by the cities of Santa Barbara, Ventura, and Oxnard, California proved to be particularly suitable for this work. In earlier attempts to study dispersion from a large-scale source, use was made of the outfall operated by Orange County, California. The variability of the flow rate through this outfall and extreme length of the diffuser section at its terminus precluded the use of this outfall in the present experiments. The physical characteristics of each outfall are summarized in Table 2. The waste water from each city receives primary treatment and intermittent chlorination before discharge to the ocean. At Santa Barbara sufficient holding capacity was available to enable the plant discharge to be held nearly constant during the time of

Table 2

Outfall Characteristics

Location	Length (feet)	Diameter (inches)	Diffuser	Average Flow Rate (MGD)	Depth (ft)
Orange County (-)	6770	78	None	120	55
Orange County	6770	78	1000 ft. long 6 in. Ports @ 16 ft. spacing	120	55
Oxnard	6800	58	384 ft. long 6 in. Ports @ 12 ft. spacing	12	65
Santa Barbara	3740	45	299 ft. long 6 in. Ports @ 10 ft. spacing	8	45
Ventura (-)	3600	36	None	2.2	35
Ventura	3600	36	56 ft. long 6 in. Ports @ 8 ft. spacing	2.2	35

Note: (-) = Without Diffuser. Diffusers were added to the the Orange County and Ventura outfalls during the course of the investigation.

the field experiments. Under such conditions the concentration of tracer dye added at the plant was held practically constant. The flow from the other two treatment plants was essentially uncontrolled and, consequently, the discharge varied during the course of these experiments. A typical discharge hydrograph for the Ventura plant is shown in Figure 3. In this case the dye tracer was added at a constant rate and the resulting concentration in the effluent varied with the waste flow. Analysis of the discharge hydrographs for all studies conducted at the Oxnard and Ventura outfalls showed that the flow varied between ± 6% to ± 30% of the average during any particular experiment. In many of these studies the flow variation was small and the dye concentration in the plant effluent was observed to be nearly constant.

At the beginning of these experiments the Ventura outfall was not equipped with a diffuser. The waste discharged directly from the open end of the outfall. The surface waste field formed by this discharge represented a small volume or quasi-point source. Recently a new outfall with a diffuser system was constructed to replace the old outfall. Studies of both outfalls were made in order to evaluate the effects of the new diffuser on the so-called initial and subsequent dilution of waste discharged.

The outfalls from both the city of Santa Barbara and Oxnard were equipped with diffusers before the present experiments began. These outfalls discharge approximately four times the flow of the Ventura outfall; consequently, the diffusers and the initial size of the surface waste fields are larger than at Ventura. The results of experiments conducted on all four outfalls were used

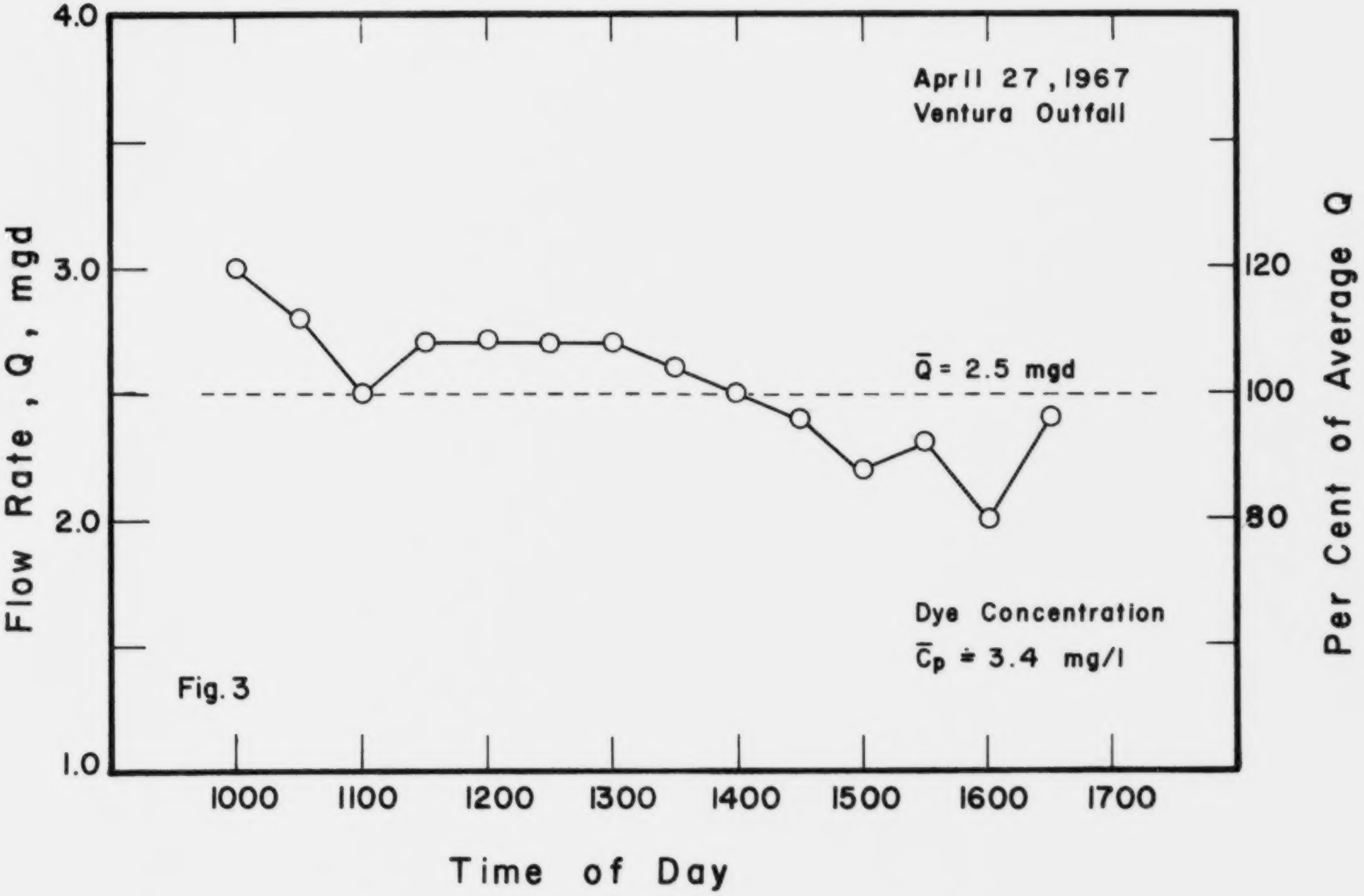

4.0
3.0
2.0
1.0
Flow Rate , Q , mgd
1000
1100
1200
1300
1400
1500
1600
1700
Time of Day
120
100
80
Per Cent of Average Q
April 27, 1967
Ventura Outfall
$\bar{Q}$ = 2.5 mgd
Dye Concentration
$\bar{C}_p \doteq 3.4$ mg/l

Fig. 3

to determine the relative effect of "source size" on the subsequent dilution of surface waste fields.

Preliminary Studies - Dye Characteristics

The physical and chemical characteristics of rhodamine B and other fluorescent tracer dyes commonly used in surface water investigations were investigated by Feurestein and Selleck (1963). These authors described the many problems involved in the use of rhodamine B dye, e.g., the effects of physical adsorption, photochemical decay, water temperature, pH, etc. The Allan Hancock Foundation (1965) conducted a similar series of experiments using waste water diluted with ocean water to concentrations commonly observed in surface waste fields. These authors found that most of the problems encountered when using rhodamine B in estuarine waters are of minor importance when this dye is used as a tracer in studies of highly diluted waste fields in the ocean. However, the effect of water temperature on the fluorescence of rhodamine B was found to be significant. One method of correcting for the temperature effect is to continually monitor the prevailing water temperature and apply an appropriate correction factor to the measured fluorescence levels. This method has been used by Pritchard and Carpenter (1960) among others. The Allan Hancock Foundation (1965) and Foxworthy et al (1966) employed a different method. In these studies of the diffusion of rhodamine B in the ocean a modified G. K. Turner model II fluorometer was used. The Instrument modification allowed simple and rapid field calibration of the unit under existing water temperature conditions. The usual calibration procedure followed was to prepare standard solutions of dye using local ocean water. These samples were used to set the desired instrument sensitivity. This procedure was repeated several times during the course of an experiment. Using this procedure the effect of temperature variation on the fluorescence of rhodamine B dye was assumed to be minimal. Since the results of the Allan Hancock Foundation studies formed the basis for the present experiments, it was assumed that rhodamine B dye was a suitable conservative tracer for use in the marine environment.

A detailed account of other problems encountered in the use of the fluorometers and other equipment employed in dye diffusion studies in the ocean is also given in the above mentioned publications.

Sampling Procedures

Over thirty individual field experiments were conducted during the past three years. The experimental procedure employed in all of these experiments was as follows:

1. Chlorination of the waste effluent, where utilized, was suspended one hour prior to, and during, all field experiments.
2. Rhodamine B dye was added to the effluent at a constant rate. The duration of the test was selected to coincide with the period of most uniform waste discharge rate.
3. Sufficient time was allowed for the tagged plant effluent to reach the ocean surface and form a quasi-steady continuous plume (see Figure 1). The time interval from start

of dye injection to beginning of field sampling in the plume ranged from one to three hours.

4. Buoys anchored at selected locations along the longitudinal axis of the plume served as markers for subsequent lateral (cross-plume) and vertical sampling runs.
5. The waste plume was sampled for both dye and bacteria concentration distribution in the lateral, vertical, and longitudinal directions. Dye concentrations were determined by continuous sampling using a G. K. Turner model II fluorometer. Sampling was accomplished by use of a deck mounted pump and an underway sampler towed from the side of the launch. The sampler was set at the depth of maximum dye concentration as determined by vertical dye profiles obtained along the axis of the plume. In most cases this depth was observed to be essentially at the water surface.
6. Bacteriological samples were obtained using presterilized plastic sample tubes and grab sampling at known time and distance intervals along the axes of the plume. All bacteriological samples were stored in the dark in portable ice chests at temperatures ranging from 8 to 10 C. The time between sampling and analysis ranged from one to six hours.
7. Wind and current speeds were determined by use of an anemometer and current meter operated from the Velero IV anchored in the test area. The anemometer was mounted approximately twenty five feet above the water surface.

The current meter employed was a combined speed and direction sensing unit. Both the current meter and anemometer were equipped with continuous recording readouts. Gross Solar radiation was measured by use of a recording pyrheliometer mounted on a gimbal table located on the upper deck of the Velero IV. Water temperatures were determined by use of thermometers and a thermistor probe operated from the research launch.

A summary of oceanographic and other experimental conditions observed in these studies is presented in Table 3.

Bacteriological Analysis

Coliform and fecal streptoccal densities were determined by accepted membrane filter techniques as outlined in Standard Methods (1965). The type of membrane filter, media, dilution water, etc., used were identical to those described in a previous section of this report. All bacteriological analyses were performed in the laboratory located on board the R. V. Velero IV. Because of limited laboratory and storage space it was found advantageous to use disposable pre-sterilized plastic petri dishes, pipets, and dilution tubes, Using these laboratory techniques and equipment it was possible to process as many as 300 samples per day during a typical 3 day study.

The typical laboratory procedure employed was as follows:

1. An estimate was made of the dilution required to produce a representative number of bacterial colonies. The optimum dilution (dilution water/sample) for coliform

Table 3

Summary of Experimental and Oceanographic Conditions

Number and Date of Study		Location	Avg.Flow Rate, $\overline{Q}$ (mgd)	Avg.Wind Speed (kts)	Avg.Current Speed (kts)	Avg.Temp (°C)	Gross Solar Energy (Cal/Cm^2)
1	1-27-66	S.B.*	8.25	17.3	0.16	12.7	132
2	1-28-66	S.B.	8.50	7.96	ND	12.8	120
3	3-17-66	S.B.	8.00	6.78	0.12	13.8	ND
4	3-18-66	S.B.	8.00	13.03	0.18	13.8	ND
5	5-13-66	S.B.	8.00	12.5	0.29	15.6	ND
6	6-10-66	Vent.*	2.25	5.4	0.21	17.7	ND
7	8-15-66	Vent.	3.50	13.0	0.20	20.3	240
8	8-16-66	Vent.	3.50	6.0	0.18	19.7	192
9	8-17-66	Vent.	3.50	9.62	0.16	18.7	146
10	11-10-66	Vent.	2.20	5.10	0.16	15.2	180
11	11-11-66	Vent.	2.20	10.6	0.16	16.2	165
12	2-23-67	Vent.	2.50	6.1	0.20	13.8	168
13	2-24-67	Vent.	2.50	3.95	0.26	13.4	114
14	4-27-67	Vent.	2.50	11.70	0.18	15.0	123
15	4-28-67	Vent.	2.50	6.60	0.25	15.3	85
16	6-7-67	Ox.*	14.30	14.3	0.11	15.5	270
17	6-8-67	Ox.	14.50	14.1	0.25	15.5	171
18	8-2AM-67	Vent.	2.20	5.9	0.13	19.5	102
19	8-2PM-67	Vent.	2.20	16.4	0.08	19.5	126
20	8-3-67	Vent.	2.20	5.10	0.37	19.5	108

*Santa Barbara; Ventura; Oxnard.

Table 3 (Cont.)

Summary of Experimental and Oceanographic Conditions

Number and Date of Study		Location	Avg. Flow Rate, $\overline{Q}$ (mgd)	Avg. Wind Speed (kts)	Avg. Current Speed (kts)	Avg. Temp. (°C)	Gross Solar Energy (Cal/Cm^2)
21	2-28-68	S.B.	9.50	10.0	0.20	16.0	212
22	2-29-68	S.B.	10.0	4.0	0.11	15.2	231.4
23	3-20A-68	S.B.	9.5	7.98	0.13	12.4	204
24	3-20B-68	S.B.	9.5	7.98	0.13	12.4	204
25	3-21-68	S.B.	10.0	6.54	0.09	13.6	320
26	6-11A-68	Vent.	2.20	11.73	0.18	12.0	243
27	6-11B-68	Vent.	2.20	13.33	0.12	12.0	280
28	9-4-68	Vent.	2.12	17.05	0.13	18.1	305
29	9-5-68	Vent.	2.34	14.36	0.22	17.9	217
30	9-6-68	Vent.	2.18	16.25	0.17	17.5	157
31	10-30-68	S.B.	10.04	9.2	0.16	16.5	257
32	10-31-68	S.B.	9.57	4.78	0.16	16.6	180
33	11-1AM-68	S.B.	10.33	5.75	0.30	16.8	69
34	11-1PM-68	S.B.	10.07	10.41	0.17	16.8	105
35	12-28-68	S.B.	9.31	2.46	0.16	12.5	54
36	12-29-68	S.B.	8.75	5.57	0.15	12.8	112
37	2-20-69	S.B.	12.13	5.62	0.14	13.2	ND
38	3-20AM-69	S.B.	10.40	6.88	0.13	14.0	176
39	3-20PM-69	S.B.	10.40	11.96	0.40	14.0	60

enumeration was found to range from 10^3 for samples taken near the origin of a particular waste plume to zero near the leading edge.

2. Duplicate aliquots from two or more dilutions were then filtered and the inoculated filters incubated for 18 to 20 hours at 35 ±2° C. for coliform and 48 hours at the same temperature for fecal streptococci.
3. A sample of the dilution water was also analyzed for the presence of the indicator organisms.

The results of these analyses were reported as the arithmetic mean bacterial concentration found at a given location in the tagged waste plume. An example of the results obtained in a study of the old Ventura outfall is shown in Table 4.

Experimental Results - Bacterial Die-Away

Coliforms. Figures 4 through 7 show the results obtained during a typical study of the new Ventura outfall conducted on November 11, 1966. Figure 4 is a vertical (composite) photograph showing the tagged waste plume as it appeared approximately three hours after the start of the test.

Measurements of dye concentrations along the longitudinal axis of this and other waste plumes showed that within the forward or leading segment of the plume the dye concentration at a given point varied considerably with time indicating unsteady conditions. This situation is brought about by advection and three-dimensional diffusion of the forward segment of the plume. A theoretical discussion of the unsteady characteristics of a continuous dye plume was presentd by Carter and Okubo (1967). In the remaining length

Table 4

Bacteriological Analysis
Ventura Outfall
November 11, 1966

Distance from Origin (1) (Feet)	Dilution	Count	Coliform Density (MFC/ml)	Average Density (MFC/ml)
0	10^2 10^3	61 4	6100 4000	5050
116	10^2 10^3	53 4	5300 4000	4150
350	10^2 10^3	41 1	4100 1000	2555
466	10^2 10^3	20 2	2000 2000	2000
582	10^1 10^2	126 11	1260 1100	1180
698	10^1 10^2	100 10	1000 1000	1000
814	10^1 10^2	77 10	770 1000	885
930	10^1 10^2	88 6	880 600	740
1047	10^1 10^2	49 4	490 400	445
1163	10^1 10^2	34 1	340 100	220
1279	10^1 10^2	32 4	320 400	360
1396	10^1 10^2	19 4	190 300	245
1512	10^1 10^2	12 1	120 100	110
1628	10^1 10^2	22 1	220 100	160
1745	10^1 10^2	6 0 (2)	60 --	60
1861	10^1 10^2	25 4	250 400	325

Table 4 (Cont.)

Distance from Origin (1) (Feet)	Dilution	Count	Coliform Density (MFC/ml)	Average Density (MFC/ml)
1977	10^1	11	110	110
	10^2	0 (2)	---	
2210	10^1	11	110	105
	10^2	1	100	
2326	10^0	52	52	46
	10^1	4	40	
2440	10^0	33	33	41.5
	10^1	5	50	
2675	10^0	31	31	30.5
	10^1	3	30	
2908	10^0	28	28	24
	10^1	2	20	
3140	10^0	15	15	12.5
	10^1	1	10	
3373	10^0	14	14	12
	10^1	1	10	
3606	10^0	10	10	10
	10^1	0 (2)	--	
3840	10^0	2	2	0
	10^1	0 (2)	--	
Dilution Water	10^0	0	--	0
	10^0	0	--	
Plant Effluent	10^5	6	6×10^5	9×10^5
	10^5	11	1.1×10^5	
	10^6	1	1×10^6	

(1) Distance along longitudinal axis of tagged waste plume.

(2) Not used in computation of average coliform density.

Ventura Outfall
November 11, 1966

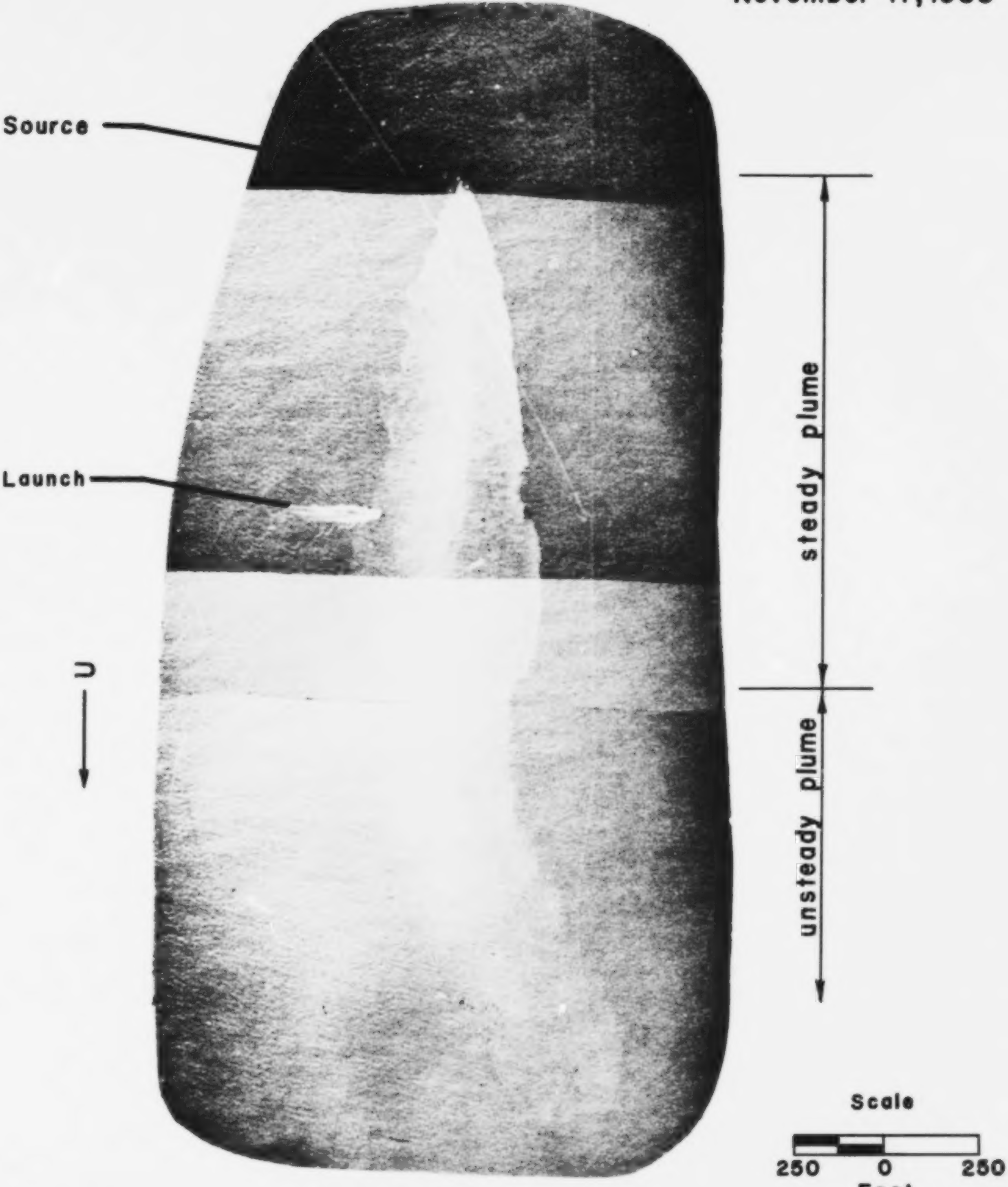

Source
Launch
U
steady plume
unsteady plume
Scale
250
0
250
Feet

Fig. 4

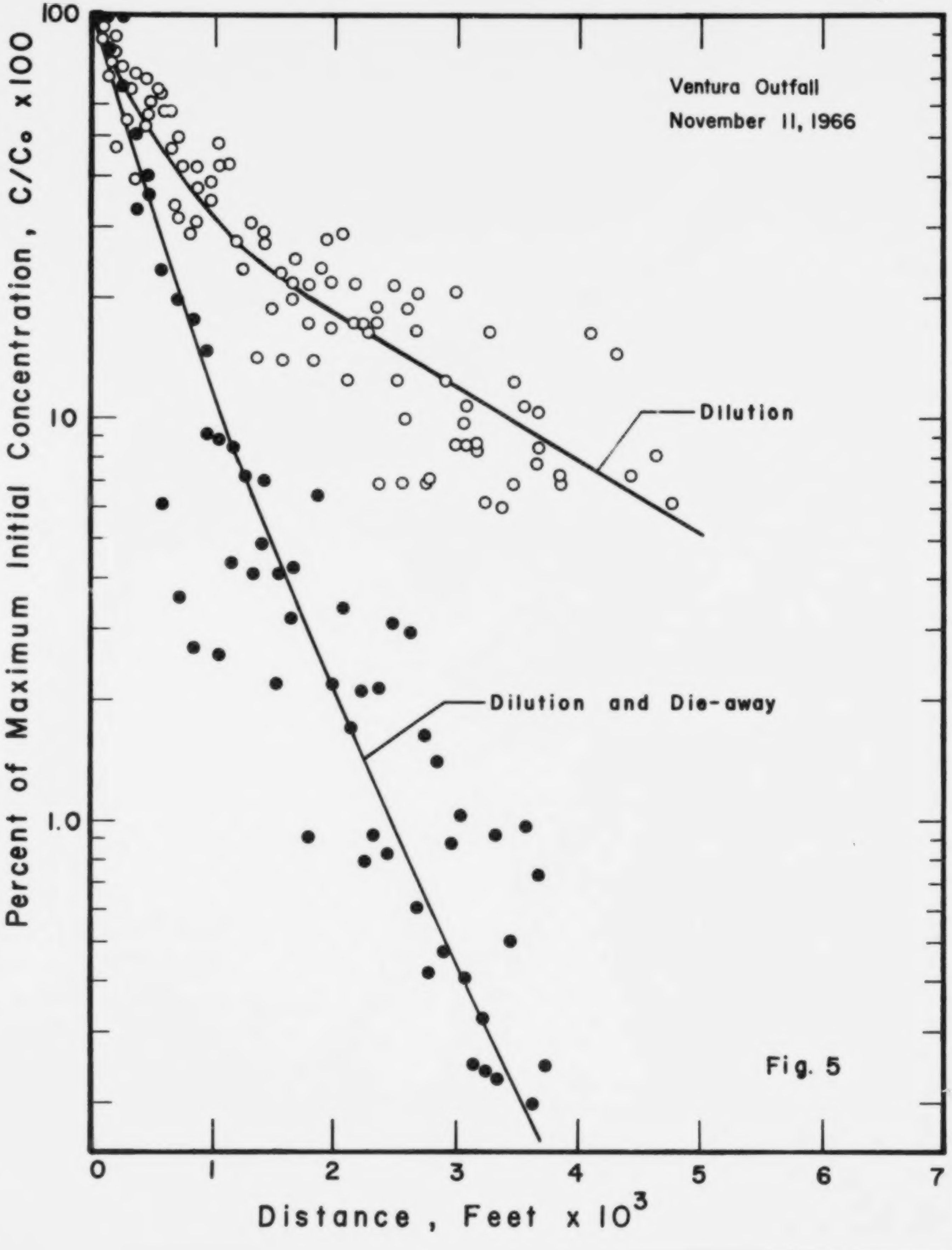
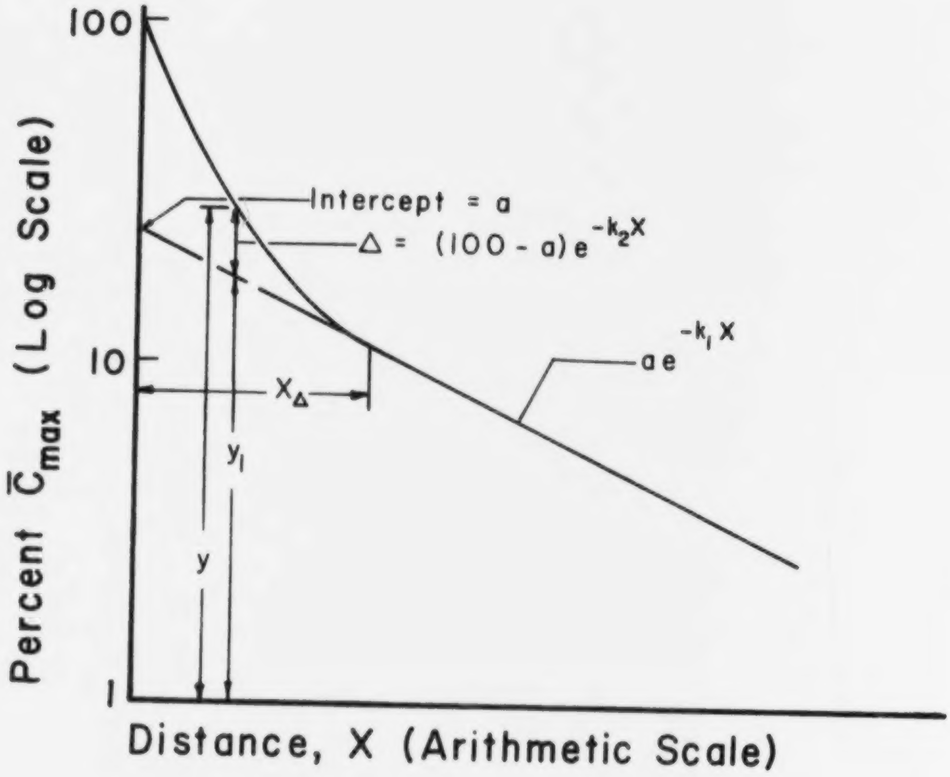

Ventura Outfall
November 11, 1966
Dilution
Dilution and Die-away
100
10
1.0
0
1
2
3
4
5
6
7
Percent of Maximum Initial Concentration, C/C₀ x100
Distance, Feet x 10³

Fig. 5



$$\% C_m = C/C_o = y = y_1 + \Delta$$
$$= ae^{-k_1 X} + (100 - a)e^{-k_2 X} \qquad (3)$$

Fig. 6

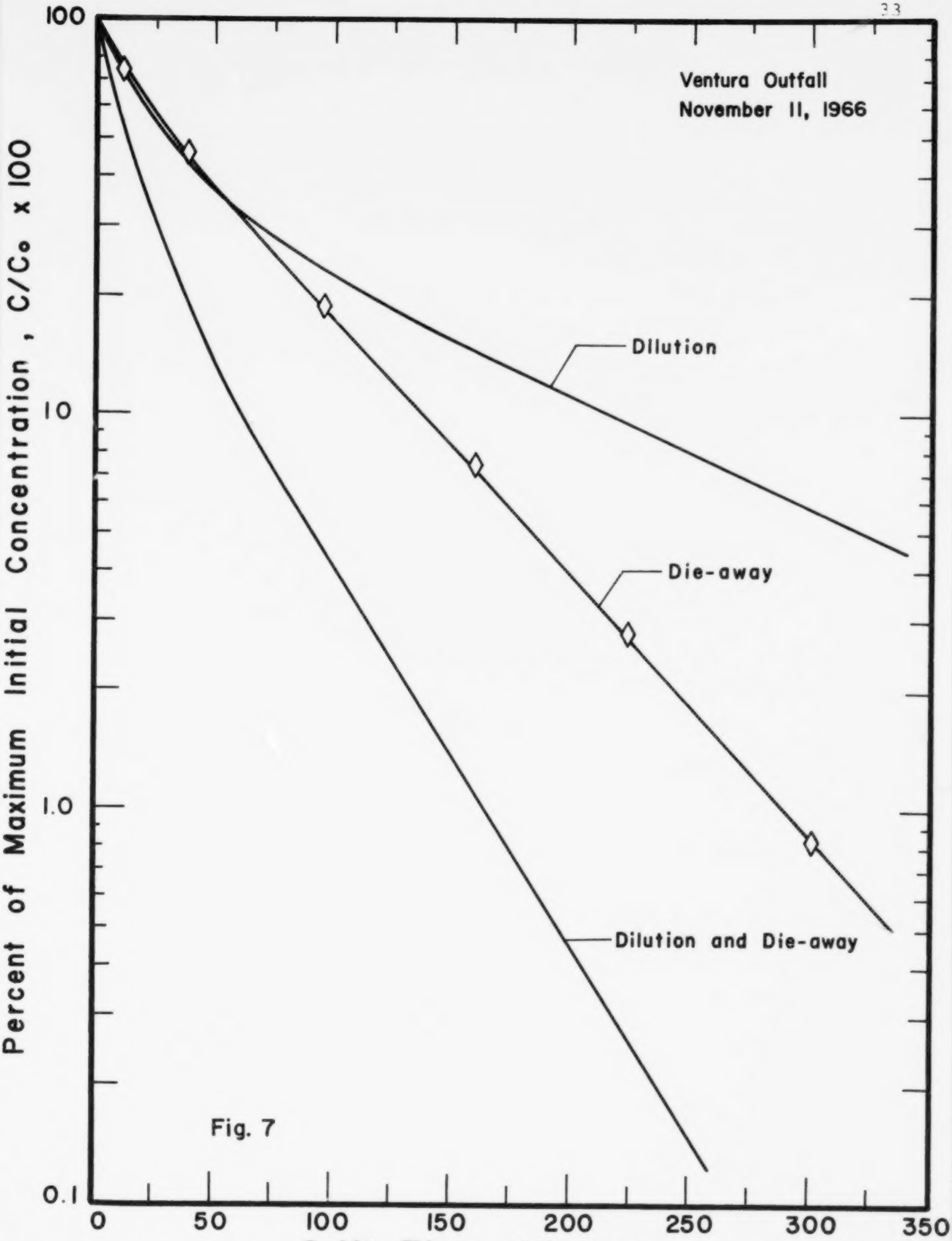

Ventura Outfall
November 11, 1966
Dilution
Die-away
Dilution and Die-away
100
10
1.0
0.1
Percent of Maximum Initial Concentration , C/Co x 100
0
50
100
150
200
250
300
350
Drift Time . Minutes

Fig. 7

of the plume the dye concentration at a point was observed to remain nearly constant with time indicating nearly steady state conditions. In this portion of the plume diffusion is essentially two-dimensional, i.e., in the lateral and vertical directions. The method used to delineate the steady and unsteady segments of a waste plume was described by Foxworthy and Barsom (1967). In brief, the method consisted of plotting the observed maximum dye and coliform concentrations along the longitudinal axis of the plume for the different times of observation and noting the locations of a sudden drop off in concentration. In the discussion which follows, all analyses were restricted to the steady state segment of the tagged waste plume.

Figure 5 is a plot of percent maximum dye and coliform concentrations at the origin vs. distance along the longitudinal axis of the plume. The decrease in dye concentration with distance represents the effect of physical dilution while that for the coliform represents the combined effects of dilution and disappearance. As discussed in a later section of this report, it was found that except in the immediate vicinity of the outfall, little or no tendency for sedimentation of coliforms was observed. Furthermore, the maximum dye and bacterial concentrations were usually found at or very near the water surface. In this case the coliform distribution shown in Figure 5 was assumed to represent the effects of physical dilution and die-away at the surface of a steady waste plume.

Analysis of this data indicated that an empirical equation of the type

$$^{C}/C_0 = ae^{-k_1x} + (100-a)e^{-k_2x} \ (\%) \tag{3}$$

adequately described the $^{C}/C_0$ vs. distance relationship. In this equation C_0 and C are the observed mean maximum dye and coliform concentrations at the origin and at any point X along the longitudinal axis of the plume, and k_1, k_2, and a are constants.

Using equation (3), the method of least squares and a digital computer, best-fit regression lines were fitted to the data for both dye and coliform distributions. The computational procedure can be described by use of Figure 6. In many cases semi-log plots of $^{C}/C_0$ vs. distance for both dye and indicator bacteria showed a rapid decrease in concentration near the origin of the plume and a slower essentially constant rate of reduction throughout the remainder of the plume. An inspection of equation (3) indicated that the first term controls the rate of reduction of $^{C}/C_0$ at large values of X. In this case it was possible to determine the best-fit equation for the portion of the plume where $^{C}/C_0$ varies (approximately) linearly with X. Least-squares analysis of the data for this segment of the plume, i.e., assuming $^{C}/C_0 = ae^{-k_1x}$, gave values of the intercept a, and the rate constant k_1. The value of Δ (Figure 6) is obtained from equation (3) as

$$\Delta = (^{C}/C_0 - ae^{-k_1x}) = (100-a)\ e^{-k_2x} \ (\%) \tag{4}$$

Equation (4) can be linearized by taking the log of both sides, thus

$$\mathrm{Ln}\,\Delta = \mathrm{Ln}\ (100-a) - k_2x \tag{5}$$

with observed values of $^{C}/C_0$ near the origin and the previously computed values of k_1 and a it was possible to estimate k_2 by the method of least-squares. It is important to note that k_2 is a constant which controls the rate at which $\underline{\Delta}$ decreases from its maximum value of (100-a) at the origin to a value of approximately zero at some arbitrary distance, X_Δ, down plume.

The best-fit regression lines shown in Figure 5 are typical of those obtained in these experiments. The scatter of the plotted points about the regression lines is attributed to two major factors: (1) patchiness of the waste plume; and (2) the difficulty of remaining in the exact zone of maximum concentration while sampling the longitudinal axis of the waste plume. Since these data were obtained from a series of sampling runs taken over an extended period of time, it seemed safe to conclude that the best-fit trend lines give a reasonably accurate picture of the longitudinal distribution of mean maximum dye and bacterial concentrations.

For purposes of comparison with the results of other experiments, the curves shown in Figure 5 were replotted to show the distribution of $(^{C}/C_0)_{max}$ with drift time. This transformation was made by simply replacing the value of X in equation (3) with its steady plume equivalent $\bar{u}t$. Here $\bar{u}$ is the mean surface current speed observed during the experiment. The results are shown in Figure 7 in which each curve is now defined by the empirical equation

$$(^{C}/C_0)_{max} = ae^{-K_1 t} + (100-a)\, e^{-K_2 t} \quad (\%) \qquad (6)$$

where K_1 and K_2 are constants having units of 1/t.

The corresponding equation for die-away was established by use of the best-fit equations for dilution and dilution and die-away together with the relationship for joint probability (frequency) distributions, that is,

$$^{C}/C_0 \text{ (die-away and dilution)} = [^{C}/C_0 \text{(dilution)}][^{C}/C_0 \text{(die-away)}] \quad (7)$$

and

$$^{C}/C_0 \text{ (die-away)} = \frac{^{C}/C_0 \text{ (dilution and die-away)}}{^{C}/C_0 \text{ (dilution)}} \quad (8)$$

Values of $^{C}/C_0$ (die-away) where computed from equation (8) for various assumed values of drift time and the results plotted as shown in Figure 7. It was found that in most cases the computed die-away relationship could be adequately defined by equation (6). A least-squares analysis was then employed to determine the constants $\underline{a}$, K_1, and K_2. The resulting trend line is also shown in Figure 7.

It is important to note that the rate of coliform die-away varied not only with time for a particular experiment but also varied considerably from experiment to experiment. The variability in die-away rates is illustrated by comparison of the data obtained from two experiments conducted at Ventura on alternate days. The results of the experiment of November 11, 1966 are shown in Figures 5 and 7. The results of the experiment conducted on November 10, 1966 are shown in Figures 8 and 9. Comparing the calculated die-away relationships shows that on November 11 (Figure 7) the rate of die-away was high near the source and decreased with time becoming nearly constant after about one hour. The results of the experiment of

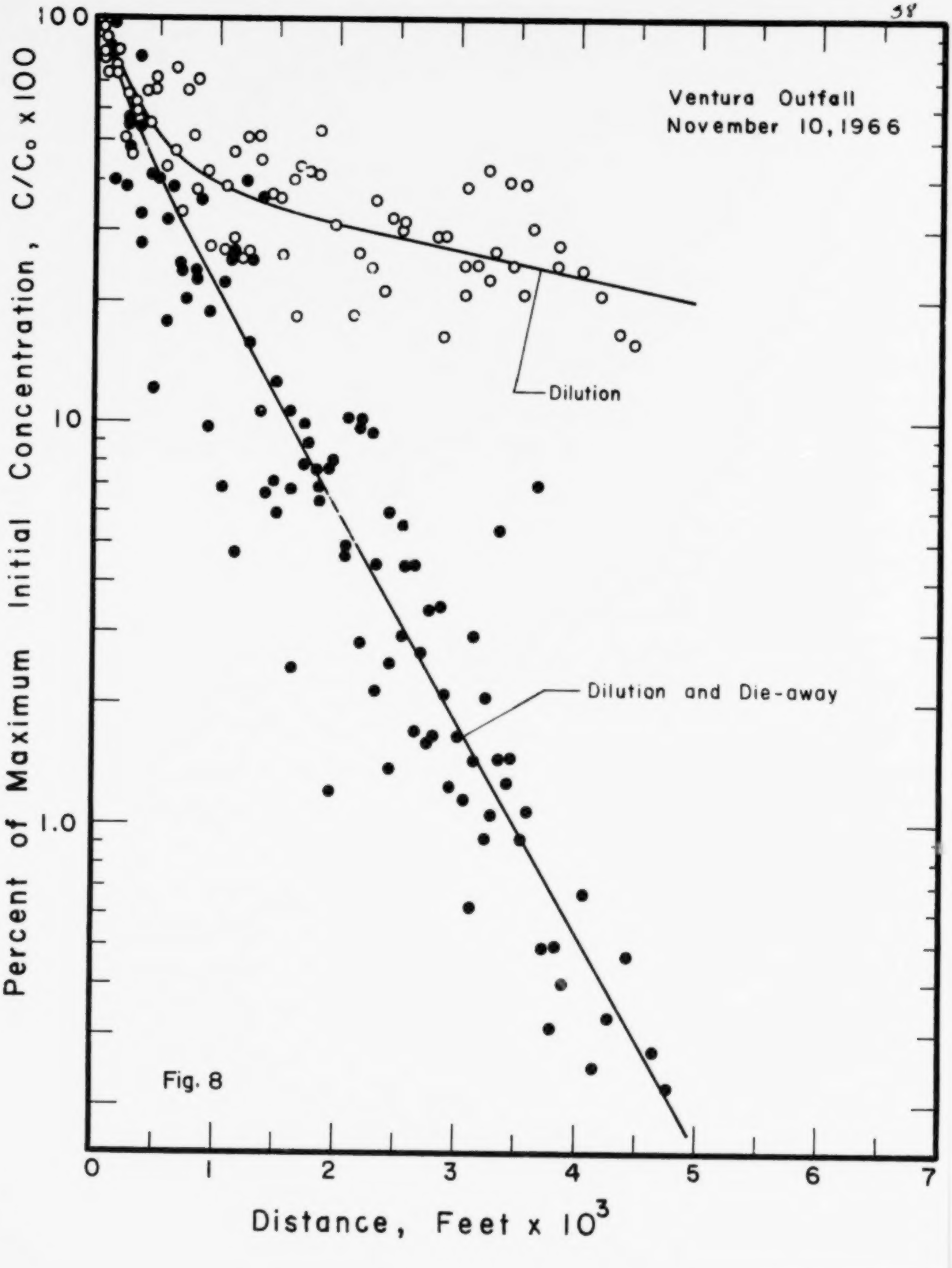


Fig. 8

Ventura Outfall
November 10, 1966
Dilution
Dilution and Die-away
Percent of Maximum Initial Concentration, $C/C_0 \times 100$
100
10
1.0
Distance, Feet $\times 10^3$
0
1
2
3
4
5
6
7

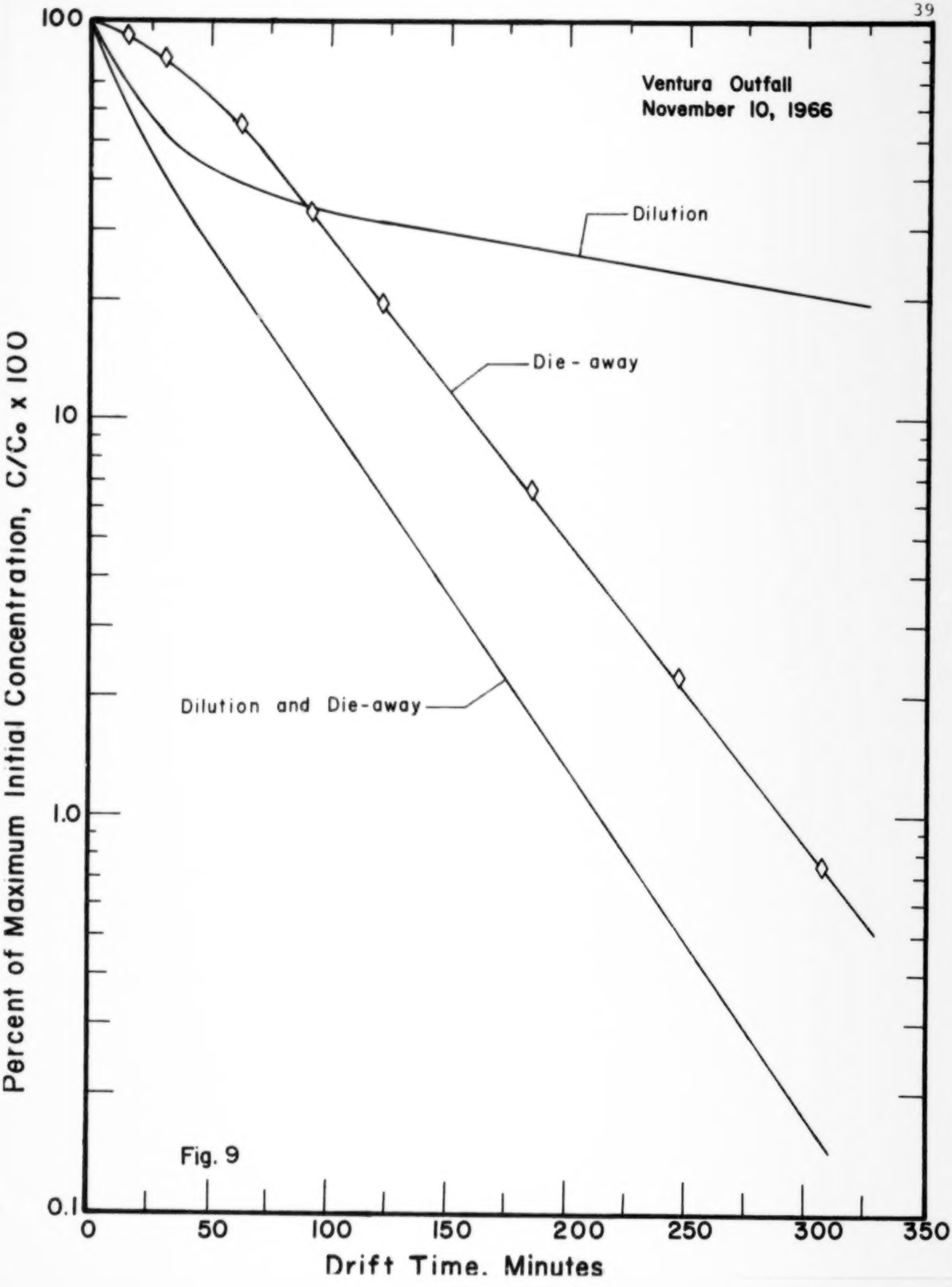

Ventura Outfall
November 10, 1966
Dilution
Die - away
Dilution and Die-away
100
10
1.0
0.1
0
50
100
150
200
250
300
350
Percent of Maximum Initial Concentration, C/C_0 x 100
Drift Time. Minutes

Fig. 9

November 10 (Figure 9) were quite different. The rate of die-away was relatively low near the source and increased with time becoming nearly constant after about 125 minutes. Comparatively speaking the rate of coliform die-away on November 10 was lower near the origin and higher near the end of the plume than that computed for the experiment of November 11.

Another interesting aspect of these results was the fact that little evidence of either growth or so-called aftergrowth of coliforms was found in either of the experiments discussed above. In other studies, however, an apparent increase in coliform concentration was observed to take place in the vicinity of the origin of the surface plume. In these experiments the so-called increasing phase continued, reaching a maximum concentration at a time ranging from about 5 to 20 minutes below the origin of the field. An example of this phenomenon is illustrated by the data shown in Figure 10 which represents the results of an experiment also conducted on the Ventura outfall on February 23, 1967. These data were obtained in the same way as that shown in Figure 7 and 8 as discussed above. It is evident that in this particular study there was an apparent growth of coliform during the first few minutes after the waste plume reached the ocean surface.

Since the die-away curve was computed from approximate best-fit relationships, the results may be questioned on the basis of errors in sampling or computational procedures. In all of the experiments conducted to date approximately one half showed a tendency for initial coliform growth. This observation together with the fact that apparent coliform growth occured at predictable times

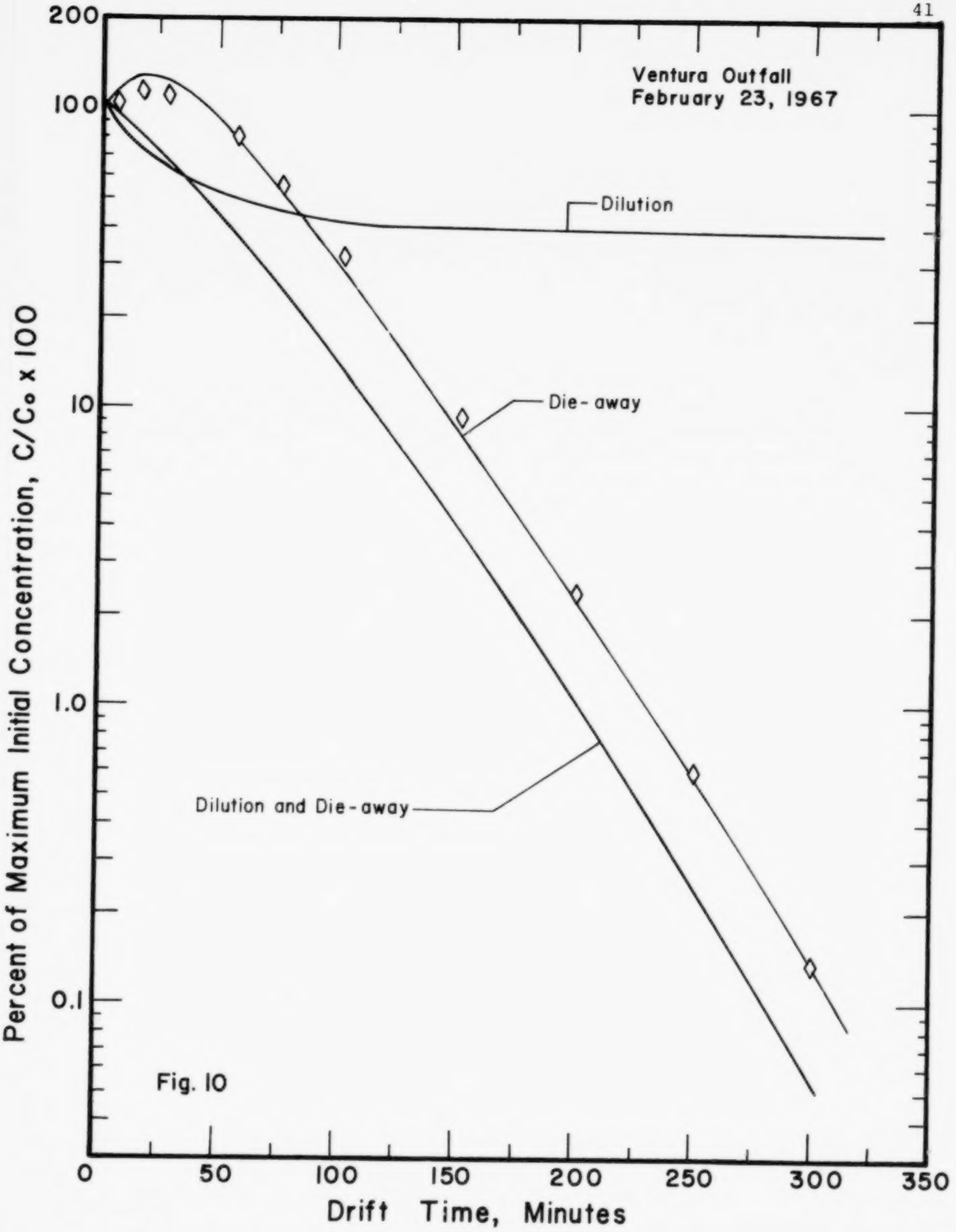

Ventura Outfall
February 23, 1967
Dilution
Die-away
Dilution and Die-away
Percent of Maximum Initial Concentration, $C/C_o \times 100$
Drift Time, Minutes
200
100
10
1.0
0.1
0
50
100
150
200
250
300
350

Fig. 10

of the year make it unlikely that sampling or computational errors were the cause of the increase in bacterial numbers.

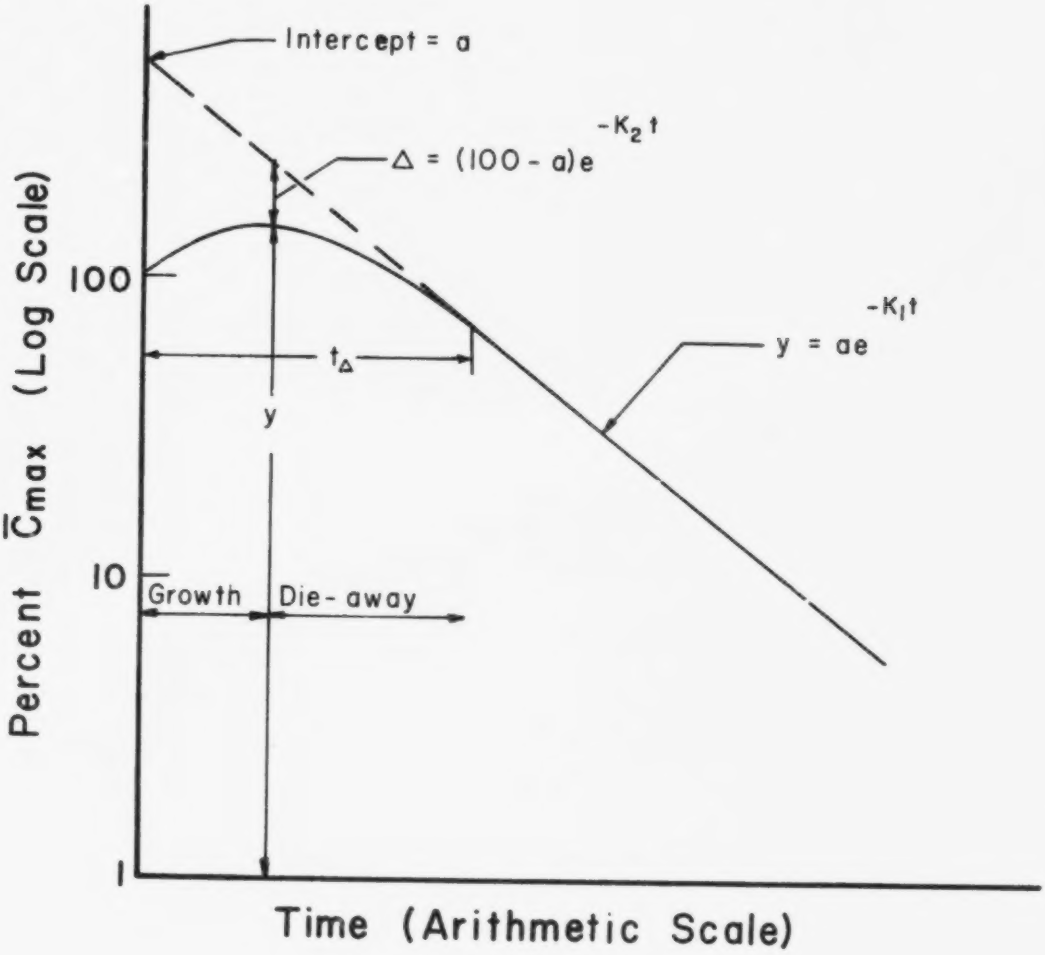
The method of obtaining the best-fit equations for coliform growth and die-away illustrated in Figures 9 and 10 was identical to that for the experiment of November 11 as shown in Figure 7. It was found that in all cases the calculated $^{C}/C_0$ (die-away) vs. time relationships were adequately described by equation (6). A graphical illustration of a typical curve of coliform growth and die-away which follows equation (6) is shown in Figure 11.

The versatility of this particular empirical formulation is demonstrated by the fact that it yields an accurate estimate of coliform die-away for the three dissimilar situations discussed above. In addition, an inspection of equation (6) shows that when the last term becomes negligible, the resulting equation is identical to Chick's Law which, as discussed previously, is commonly assumed to apply to coliform die-away in the ocean.

The above findings are not unique to the present research. Frost and Streeter (1934) proposed a so-called two-fraction equation similar to equation (3) which satisfactorily fitted the descending portion of a typical coliform die-away curve for river water. Their equation is of the form

$$y = a(10^{-bx}) + C\ (10^{-dx}) \tag{9}$$

where y̲ is the residual number of bacteria remaining after time X; a̲ is considered to be the fraction of the initial population decreasing at a rate b̲; and C is the fraction of the initial population decreasing


Intercept = a
Δ = (100 - a)e$^{-K_2 t}$
y = ae$^{-K_1 t}$
Percent $\bar{C}_{max}$ (Log Scale)
100
10
1
t_Δ
y
Growth
Die-away
Time (Arithmetic Scale)

$$y = C/C_o = ae^{-K_1 t} - \Delta$$

$$= ae^{-K_1 t} + (100 - a)e^{-K_2 t} \qquad (6)$$

Note that the second term becomes negative in this case since "a" > 100%.

Fig. 11

at rate d. Converting equation (6) to the base 10 and redesignating the constants yields a relationship identical to equation (9).

Streeter (1934) in a later investigation, proposed an equation which fitted both the observed growth and die-away phases of coliform curves for river waters. This equation has the form

$$y = (y_a - b_a)\ 10^{-kt^n} + [(b_a - C_a)\ 10^{-k_1 t} + C_a (10)^{-k_2 t}] \tag{10}$$

where y is the residual number remaining after time t; and $(y_a - b_a)$, $(b_a - C_a)$, and C_a are fractions of the initial coliform population decreasing at rates k, k_1, and k_2.

Methods for computing the values of the constants in the above equations together with typical values for river waters were presented by the authors.

A detailed discussion of other formulations of bacterial die-away applicable to laboratory and field experiments was given by Pearson (1956) and Hyperion Engineers (1957).

The significant point brought out in the present studies is that empirical equations were found which satisfactorily described the complete space-time distribution of mean coliform die-away for a variety of observed conditions. In this respect equation (3) or its equivalent (6) was found to be more general than first proposed.

A summary of the constants a, K_1, and K_2 obtained for all coliform die-away curves is presented in Table 5.

Fecal Streptococci. During the past year the scope of the investigation was extended to include studies of the fate of fecal streptococci as well as coliform bacteria discharged into the ocean. A series of parallel experiments were run to ascertain

Table 5

Summary of Coliform Parameters

Number and Date of Study		$K_1 \times 10^{-2}$ (min^{-1})	$K_2 \times 10^{-2}$ (min^{-1})	a (%)	$(dy/dt)_0$ (%/min.) [1]	Density $C_0 \times 10^3$ (MFC/ml) [1]	T_{90} (min)	Avg. Coliform Density at plant (MFC/ml)
1	1-27-66	4.01	5.30	1100	8.89	2.00	125	ND
2	1-28-66	2.99	3.84	756	2.59	1.06	133	ND
3	3-17-66	2.71	4.00	1090	10.06	2.84	178	1.03×10^6
4	3-18-66	3.59	4.36	800	1.80	2.76	122	7.05×10^5
5	5-13-66	2.67	3.82	290	-0.48	0.80	123	ND
6	6-10-66	1.94	7.64	23.5	-6.30	15.00	45	8.0×10^5
7	8-15-66	2.06	6.28	60	-3.75	21.00	88	1.6×10^6
8	8-16-66	0.583	3.63	38.7	-2.46	27.33	230	ND
9	8-17-66	0.635	6.46	21.8	-5.19	19.00	123	ND
10	11-10-66	1.78	4.00	178	-0.05	4.25	160	2.3×10^6
11	11-11-66	1.51	9.96	80.2	-3.18	4.16	140	9.0×10^5
12	2-23-67	2.89	4.02	700	3.89	2.28	145	1.6×10^6
13	2-24-67	5.40	6.14	1900	8.00	4.38	96	ND
14	4-27-67	2.64	4.00	32.5	-3.56	7.83	48	1.3×10^6
15	4-28-67	0.94	5.24	21.5	-4.32	5.22	85	ND
16	6-7-67	1.81	2.70	676	3.31	6.24		4.0×10^6
17	6-8-67	3.56	4.70	890	5.45	9.95	120	ND
18	8-2AM-67	1.22	10.50	50	5.86	15.16	125	ND
19	8-2PM-67	1.40	6.29	19.1	-5.36	32.88	69	ND
20	8-3-67	1.67	10.24	26	-8.00	33.77	58	ND
21	2-28-68	0.814	2.90	45	-1.97	2.00	178	2.3×10^5

[1] Computed and observed values at origin of surface plume above outfall

Table 5

Summary of Coliform Parameters

Number and Date of Study		$K_1 x10^{-2}$ (min^{-1})	$K_2 x10^{-2}$ (min^{-1})	a (%)	$(dy/dt)_0$ (%/min.) [1]	Density $C_0 x10^3$ (MFC/ml) [1]	T_{90} (min)	Avg. Coliform Density at plant (MFC/ml)
22	2-29-68	2.30	3.77	221	-0.52	4.65	133	4.3 x 10^5
23	3-20A-68	4.74	10.50	280	5.63	3.33	70	7.4 x 10^5
24	3-20B-68	1.80	3.33	379	2.47	3.33	210	7.4 x 10^5
25	3-21-68	2.20	7.50	195	2.84	5.46	135	5.8 x 10^5
26	6-11A-68	4.04	12.13	11.5	-11.20	7.63	23	1.95 x 10^6
27	6-11B-68	1.12	6.36	150	1.50	11.61	243	1.95 x 10^6
28	9-4-68	1.17	11.73	109.5	-0.29	18.72	204	3.93 x 10^6
29	9-5-68	2.38	4.45	158	-1.18	4.92	115	1.54 x 10^6
30	9-6-68	2.51	5.70	131	-1.52	12.31	103	ND
31	10-30-68	2.86	3.24	3000	8.00	2.31	206	ND
32	10-31-68	0.22	7.03	76.14	-1.98	2.38	NA	7.5 x 10^5
33	11-1AM-68	2.55	11.60	121	-0.65	5.41	98	7.5 x 10^5
34	11-1PM-68	0.97	4.80	121	-0.16	3.47	259	7.5 x 10^5
35	12-28-68	2.04	2.57	1500	5.38	4.26	245	9.67 x 10^5
36	12-29-68	0.76	7.00	123	0.68	3.14	328	1.3 x 10^6
37	2-20-68	2.83	3.00	9018	12.33	2.84	210	6.2 x 10^5
38	3-20AM-69	2.42	9.71	220	5.13	2.93	128	9.8 x 10^5
39	3-20PM-69	2.49	3.04	670	0.65	2.88	170	9.8 x 10^5

[1] Computed and observed values at origin of surface plume above outfall

the relative die-away characteristics of these indicator systems dispersing under identical field conditions. The sampling and analytical procedures employed in these studies were identical to those described above. Estimates of coliform and fecal streptococci densities were obtained by subjecting separate aliquots of the same water sample to membrane filter analysis.

The partial results of one parallel experiment are shown in Figure 12. For reasons of clarity only the resulting best-fit curves for die-away are shown. The methods used to derive the indicated relationships were the same as those discussed earlier. It was found that the decrease in maximum concentration of fecal streptococci, as for coliforms, was adequately defined by equations (3) and (6). From the data presented in Figure 12 it is evident that in this experiment the initial mean maximum coliform density was approximately two orders of magnitude greater than the corresponding fecal streptococcal density. The rate of decrease of coliforms was, however, much greater than that for the fecal streptococci. Because of the different rates of decrease the densities of the two indicator groups reached the same level after approximately 260 minutes travel time; from there on the coliform concentration became increasingly less than that of the fecal streptococci. Similar results were obtained in other experiments as evidenced by the relative values of $\bar{C}_0$, K_1, K_2, and $\underline{a}$ presented in Tables 5 and 6.

Another important finding of these later experiments was the fact that of all the experiments conducted involving fecal streptococci approximately one half showed an initial increase in numbers

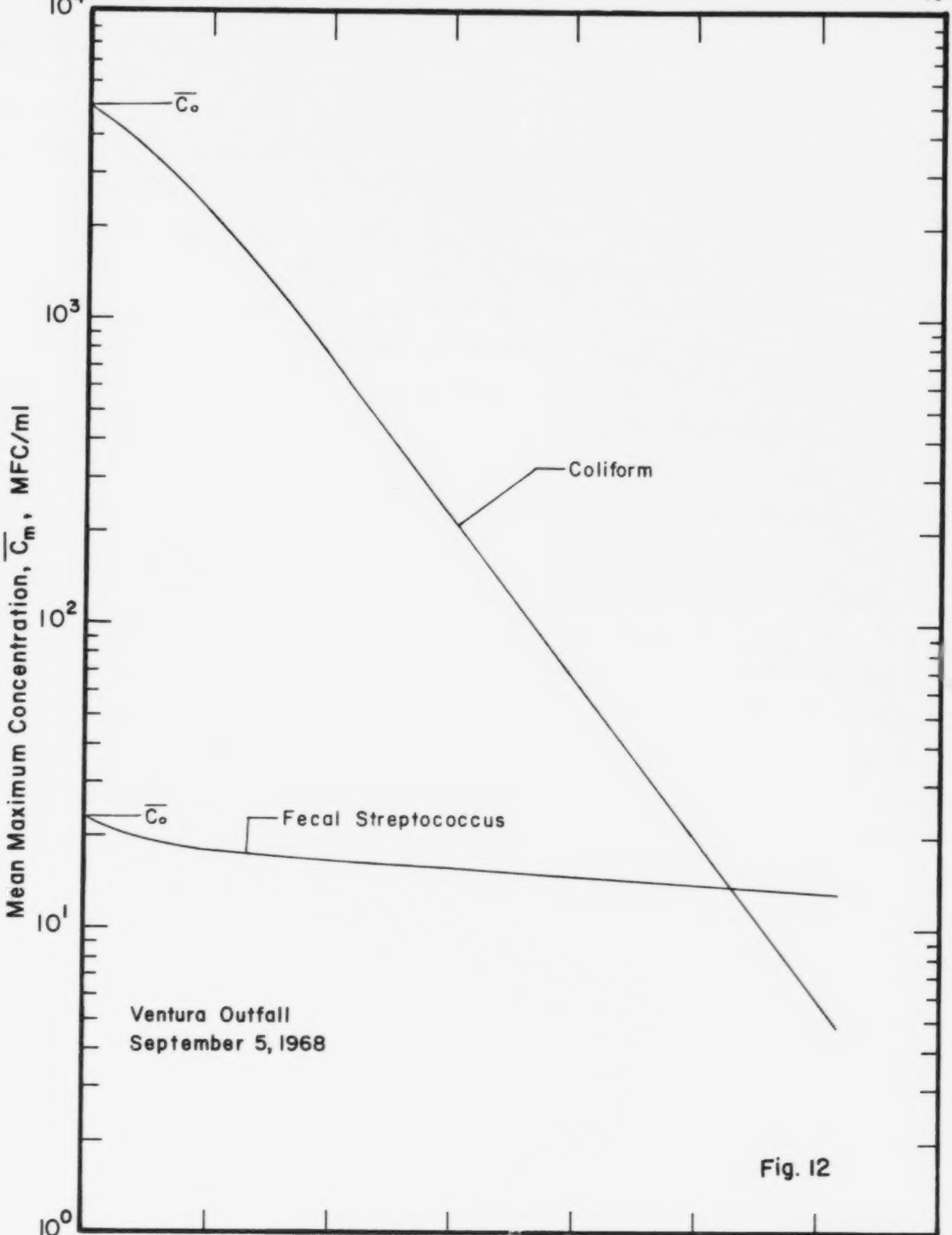

10^4
10^3
10^2
10^1
10^0
Mean Maximum Concentration, $\overline{C_m}$, MFC/ml
$\overline{C_o}$
Coliform
$\overline{C_o}$
Fecal Streptococcus
Ventura Outfall
September 5, 1968
0
1
2
3
Drift Time. minutes X 10^2

Fig. 12

Table 6

Summary of *Fecal Streptococcus* Parameters

Number and Date of Study		$K_1 x 10^{-2}$ (min^{-1})	$K_2 x 10^{-2}$ (min^{-1})	a (%)	$(dy/dt)_0$ (%/min.)	Density C_0 (MFC/ml)	Avg. Temp. (°C)	Avg. Fecal Strep. Density at plant (MFC/ml)
14	4-27-67	-0.51	6.66	22.8	-5.02	87.50	15.0	1.21×10^4
15	4-28-67	1.71	2.98	129	-1.35	85.67	15.3	ND
16	6-7-67	0.66	1.77	220	0.66	55.13	15.5	2.63×10^3
28	9-4-68	0.60	4.30	120	0.14	55.38	18.1	2.63×10^4
29	9-5-68	0.12	3.92	84	-0.73	22.43	17.9	3.98×10^4
30	9-6-68	-0.79	9.54	45.9	-4.80	38.7	17.5	ND
31	10-30-68	ND	ND	ND	ND	ND	16.5	ND
32	10-31-68	ND	ND	ND	ND	ND	16.6	6.72×10^3
33	11-1AM-68	2.28	14.9	120	0.24	116.75	16.8	2.18×10^3
34	11-1PM-68	0.92	2.32	169	0.04	60.25	16.8	2.18×10^3
35	12-28-68	-0.04	3.60	68.8	-1.10	101	12.5	1.73×10^3
36	12-29-68	1.18	6.20	121	-0.13	113	12.8	5.25×10^3
37	2-20-69	0.20	1.61	116	0.02	93	13.2	6.5×10^3
38	3-20AM-69	0.80	20.82	110	1.20	66	14.0	1.02×10^4
39	3-20PM-69	-0.76	13.20	54.5	-5.60	46	14.0	1.02×10^4

near the origin of the surface plumes. As will be discussed later, an initial growth of both indicator groups is shown by positive values of the initial rate of change of density tabulated in Tables 5 and 6.

The results of the experiments discussed above appear to indicate that the fecal streptococcal group may be a superior indicator of enteric bacterial pollution in the sea. That is, since both indicator groups show similar tendencies for initial growth and die-away, the best indicator system is the one which exhibits the highest overall resistance to the adverse effects of the marine environment; namely, the fecal streptococci. The outcome of additional experiments, however, showed this tentative conclusion to be erroneous. This is demonstrated by the results of the experiment depicted in Figure 13. In this particular study the fecal streptococcal concentration decreased initially reaching a minimum value after about 25 minutes travel time. After this time the density increased steadily eventually exceeding the initial maximum concentration. On the other hand the coliform density decreased continuously along the plume becoming equal to the fecal streptococcal concentration after about 140 minutes travel time. Beyond this point the coliform concentration became steadily less than that for the fecal streptococci.

Before further discussion of these results it should be noted that the best-fit curve for fecal streptococcal concentration shown in Figure 13 followed equations similar to (3) and (6) except for a positive value of the rate constant K_1. A definition sketch of the appropriate empirical formulation for this case is shown in Figure 14.

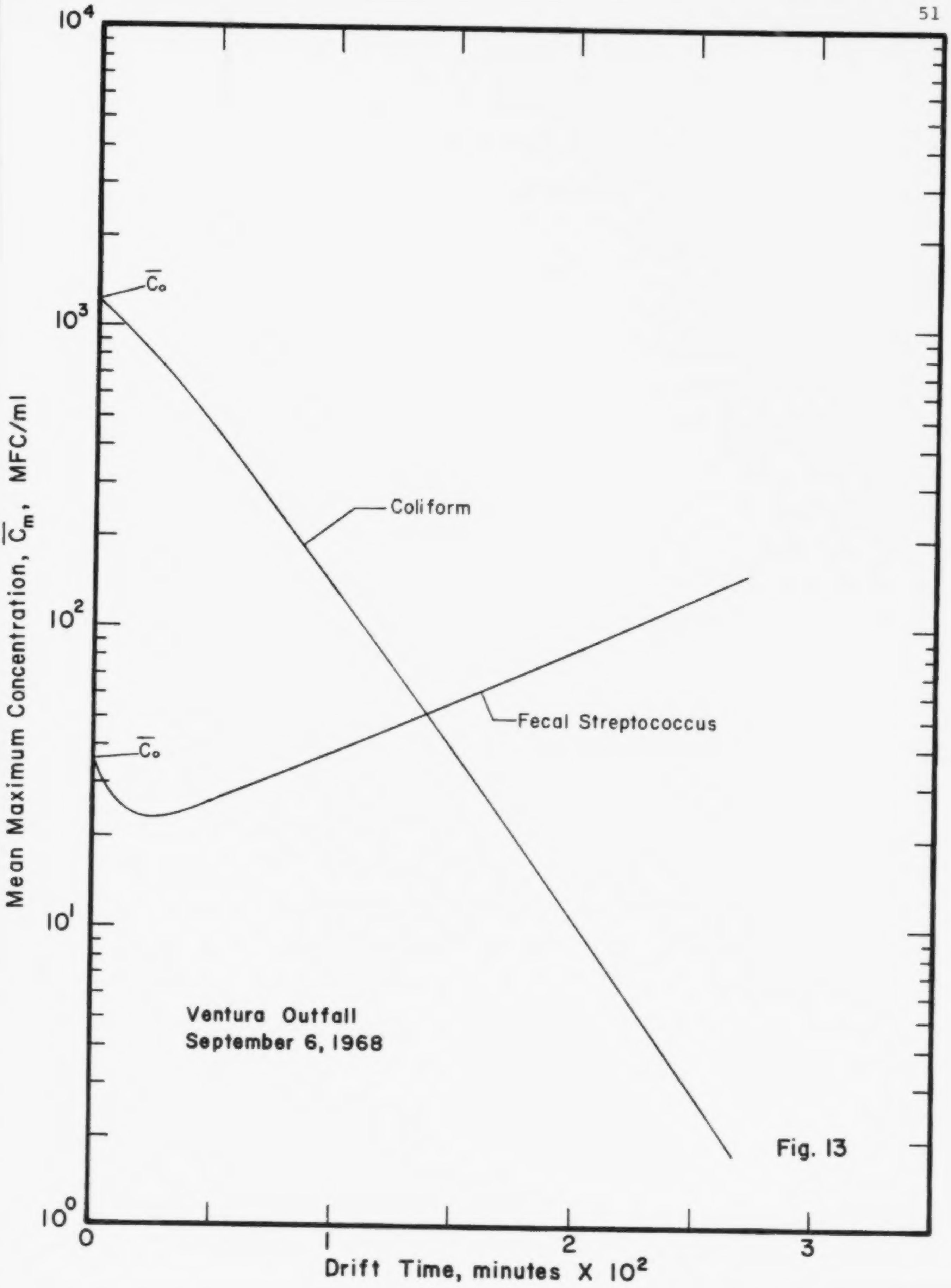
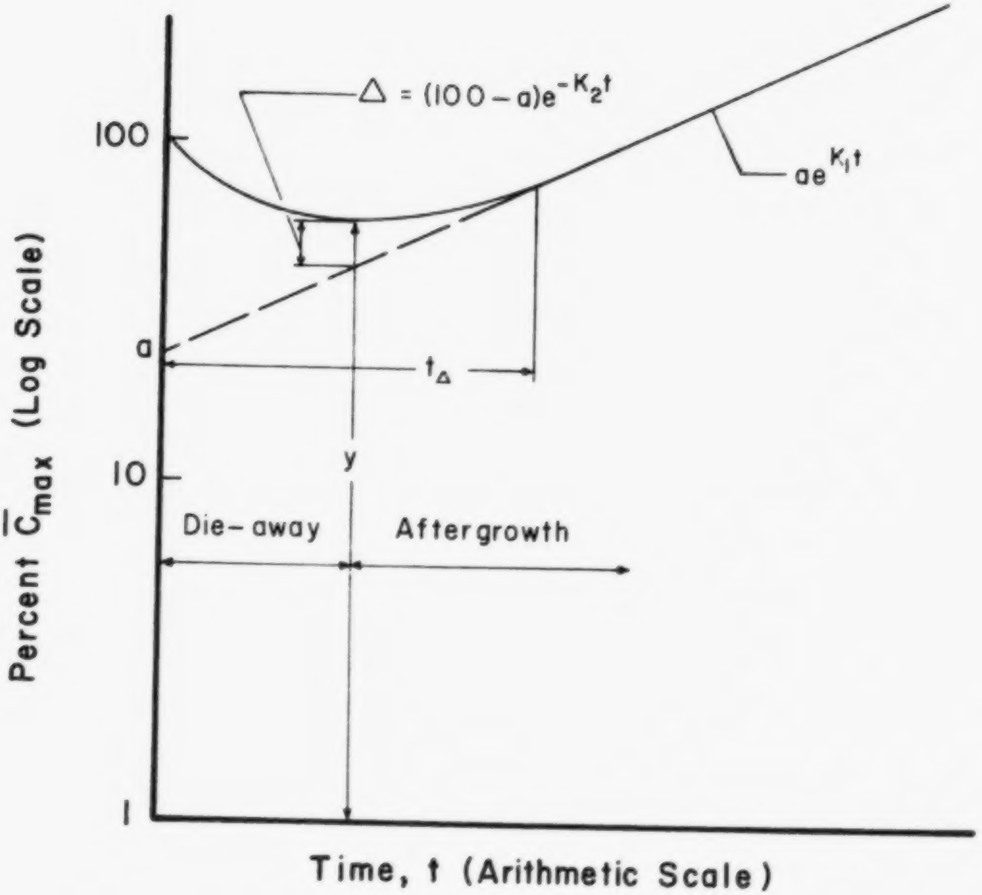

10^4
10^3
10^2
10^1
10^0
$\overline{C}_o$
$\overline{C}_o$
Coliform
Fecal Streptococcus
0
1
2
3
Mean Maximum Concentration, $\overline{C}_m$, MFC/ml
Drift Time, minutes X 10^2
Ventura Outfall
September 6, 1968

Fig. 13



$$y = C/C_o = ae^{K_1 t} + \Delta$$
$$= ae^{K_1 t} + (100-a)e^{-K_2 t} \qquad (6a)$$

Fig. 14

Regrowth or so-called aftergrowth of fecal streptococci was also observed in other experiments as evidenced by the positive values of K_1 shown in Table 6. The reasons for this phenomenon are not readily apparent. One thing appears certain, however, it was not because of an input of fecal streptococci from background waters surrounding the waste plumes. Water samples taken from background areas around the plumes gave no evidence of the presence of either fecal streptococci or coliform organisms. It is possible that the above results were due to sampling errors or, as suggested by Ballantine and Kittrell (1968), that the increase in bacterial numbers was due to the disintegration of waste solids. Such problems would be expected to have equal influence on the observed concentrations of both indicator systems. That this was not the case in these experiments is evidenced by the data presented in Figure 13 and Tables 5 and 6. These findings cast doubt on the effectiveness of the fecal streptococcal group as an indicator of enteric bacterial pollution in the ocean.

It is also interesting to note that the results of the present field experiments disagree with the laboratory results obtained by Hanes and Fragala (1967). While these authors found that in high concentrations of sea water (67% sea water by volume) fecal streptococci were more resistant than coliforms, they observed no growth or aftergrowth of these indicator organisms. The reason(s) for this apparent discrepancy in results is not known, except to reiterate what was discussed earlier; namely, the inability of laboratory experiments to duplicate fully what happens in a dynamic natural environment.

Theoretical Models of Oceanic Dispersion

Various mathematical models of dispersion of waste waters continuously discharged into the ocean have been proposed in the past. Many of these formulations are empirical in nature and therefore apply to specific environmental conditions. Hence, the applicability of these models to the results of the present experiments was not investigated.

Recent advances in the theoretical concepts of turbulent diffusion have resulted in the formulation of more general theoretical models of the dispersion phenomenon. In particular, the equations proposed by Brooks (1959) have found wide acceptance in the design of submarine outfalls. Brooks' equations are solutions of the basic differential equation for horizontal dispersion of material discharged from a continuous line source in a steady current and incorporate both constant and variable coefficients of horizontal diffusivity. Recently Foxworthy et al (1966), following the earlier work of Gifford (1955, 1959), proposed a series of statistical models for multi-dimensional dispersion of a steady continuous waste plume discharged from point and large volume sources. These equations were written in terms of so-called mean-square dispersion parameters, i.e., variances of the multi-dimensional concentration distributions, instead of diffusivity coefficients. These authors attempted to assess the validity of the proposed models by use of data collected in field experiments on the dispersion characteristics of a large-scale continuous waste plume tagged with a conservative tracer dye. Their results indicated that the proposed equations could be used to give a satisfactory description of the concentration distribution of any conservative constituent of wastewaters.

Statistical Models

In most of the experiments conducted to date the diffusion of the waste plumes was observed to be both one- and two-dimensional, i.e., in the lateral and vertical coordinate directions. Under such conditions the multi-dimensional statistical models proposed by Foxworthy, et al are directly applicable and hence will be discussed at this time. These authors considered the case of the steady discharge of wastewater from a continuous volume source in a horizontally and vertically unbounded ocean. A volume source, considered to be composed of groups of many continuous point-sources, was assumed to accurately describe the physical shape of a waste plume formed at the ocean surface above the terminus of a submarine outfall.

An equation for the mean concentration of a conservative waste at any point x, y, z within a steady surface plume diffusing in the lateral and vertical directions was given by the above authors as

$$C = \frac{Q}{\pi U \left[S_y^2 + \sigma_{yo}^2\right]^{1/2} \left[S_z^2 + \sigma_{zo}^2\right]^{1/2}} \exp - \left[\frac{y^2}{S_y^2 + \sigma_{yo}^2} + \frac{z^2}{S_z^2 + \sigma_{zo}^2}\right] \quad (11)$$

where

Q = average waste flow rate, $^{lb}/_{hr}$

U = average current speed, $^{ft}/_{hr}$

S^2 = the mean variance of the waste concentration distribution in a given coordinate direction as a function of distance (X) along a plume discharged from a point-source, ft^2

σ_0^2 = the mean coordinate variance of waste concentration distribution at the origin of a large-scale plume, ft^2

x, y, z = coordinate directions; x along the longitudinal axis of the plume; y along the lateral axis perpendicular to x; and z along the vertical axis perpendicular to x and y.

An approximate relationship between diffusion parameters for a plume with relatively large initial size and those of a point-source is given by

$$\sigma^2 = \sigma_0^2 + S^2 \tag{12}$$

In other words, the variance of the material distribution in a given coordinate direction (as a function of distance or time) is assumed to be equal to the sum of the variances of a point source and that observed at the origin of a surface waste plume.

A primary concern in the design of any outfall system is the accurate prediction of the spatial distribution of maximum waste concentration. The mean maximum concentration along the longitudinal axis of a surface waste plume is obtained from equation (11) by setting $y = z = 0$, thus

$$C_m = \frac{Q}{\pi U \left[S_y^2 + \sigma_{y0}^2\right]^{1/2} \left[S_z^2 + \sigma_{z0}^2\right]^{1/2}} \tag{13}$$

Multiplying the bracketed quantities in the denominator by σ_0^2/σ_0^2 and simplifying yields

$$C_m = \frac{Q}{\pi U \sigma_{yo} \sigma_{zo} \left[\frac{S_y^2}{\sigma_{yo}^2} + 1\right]^{1/2} \left[\frac{S_z^2}{\sigma_{zo}^2} + 1\right]^{1/2}} \tag{14}$$

The diffusion parameters S^2 are functions of distance such that $S^2 \rightarrow 0$ as $x \rightarrow 0$. Hence at the origin of the plume the mean maximum central concentration is given as

$$C_m = C_o = \frac{Q}{\pi U \sigma_{yo} \sigma_{zo}} \tag{15}$$

substituting equation (15) into (14) and rearranging yields

$$C_m = \frac{C_o}{\left[\frac{S_y^2}{\sigma_{yo}^2} + 1\right]^{1/2} \left[\frac{S_z^2}{\sigma_{zo}^2} + 1\right]^{1/2}} \tag{16}$$

In the event vertical diffusion of the plume is negligible and, as was observed in some of the present experiments, the vertical distribution of material remains normal -- the approximate equation for the mean maximum concentration is

$$C_m \doteq \frac{C_o}{\left[\frac{S_y^2}{\sigma_{yo}^2} + 1\right]^{1/2}} \tag{17}$$

where C_0 is defined by equation (15).

It is important to note that the above equations are for mean maximum concentrations. Csanady, (1966) showed that the instantaneous peak concentration at a given lateral cross-section of a continuous dye plume was approximately equal to twice the value of the mean maximum concentration. These results can be applied to the above equations to yield estimates of the instantaneous peak centerline waste concentrations.

When the dispersing waste material is non-conservative, the foregoing equations can be modified by simply multiplying the appropriate equation by a term which accounts for the rate of decay, i.e.,

$$C\ (\text{non-conservative}) = [C(\text{conservative})][C\ (\text{decay})] \tag{18}$$

For the case of indicator bacteria the appropriate decay or die-away equation is given by equation (3) or its steady plume equivalent, equation (6). Thus, for conditions of combined horizontal and vertical diffusion of bacteria the mean maximum concentration along the central axis of a steady plume is

$$C_m = \frac{C_o}{\left[\frac{S_y^2}{\sigma_{yo}^2} + 1\right]^{1/2} \left[\frac{S_z^2}{\sigma_{zo}^2} + 1\right]^{1/2}} \left[a e^{-k_1 x} + (100-a) e^{-k_2 x}\right] \tag{19}$$

where C_0 is the initial mean maximum bacterial density in numbers per unit volume. Values of C_0 can be obtained from equation (15) using Q as the mean discharge rate in numbers per unit time.

The corresponding equation for purely horizontal dispersion and die-away is

$$C_m \doteq \frac{C_o}{\left[\frac{S^2}{\sigma_{yo}^2} + 1\right]^{1/2}} \left[a e^{-k_1 x} + (100-a) e^{-k_2 x}\right] \tag{20}$$

Concentration Distributions

An essential a priori assumption made in the derivation of the above equations is that the distribution of diffusing material is normal or Gaussian. The validity of this assumption for continuous dye plumes was discussed by Csanady (1966) and Foxworthy, et al (1966). These authors showed that in the case of a continuous *point* release, the mean concentration distributions in the lateral and vertical directions of the plume were approximately normal. Csanady's results are particularly interesting since he showed that even though the instantaneous lateral dye concentration profiles were, in many cases, strongly skewed, the mean profiles computed over a long period of time were nearly normal. Csanady's results were obtained from a series of 25 lateral sampling runs at a given cross-section of a continuous dye plume.

Foxworthy, et al also presented the results of two experiments in which the entire waste flow from the Orange County, California treatment plant was tagged with dye before discharge to the ocean. The results of these experiments were rather inconclusive in that in one case the lateral and vertical profiles of mean dye concentration were approximately normal and in the other case the lateral profiles, especially near the plume origin, were strongly skewed. In these studies the large waste flow rate ($\overline{Q}$ = 100 millon gallons per day) and correspondingly high rate of dye consumption limited the time of the experiment to a few hours duration. The large size of these waste fields resulted in longer sampling runs; consequently, it was possible to obtain only limited information on the space-time distribution of dye concentration. The above authors also noted that the lack of a diffuser at the terminus of the outfall may have been responsible for the apparent non-Gaussian shape of the lateral concentration profiles.

Although time was still a limiting factor in the present experiments, in some cases it was possible to obtain a more complete record of the spatial distribution of dye concentration than observed in the studies at Orange County. The partial results of one experiment on the old Ventura outfall (without diffuser) are shown in Figures 15 and 16. In this case six separate lateral and vertical sampling runs were made at various locations along the tagged waste field. The instantaneous dye concentration distributions were obtained from the data recorded on the fluorometer readout and the known launch speed. These data were then plotted on tracing paper and the mean values for all sampling runs obtained by first matching the location of the points of instantaneous peak concentrations. The approximate values of the mean variances, $\sigma_{y,z}^2$, were then computed from these profiles by use of the equation for the second-moment given by

$$\sigma^2 = \frac{\sum_{i=1}^{n} f_i x_i^2 - \frac{\left(\sum_{i=1}^{n} f_i x_i\right)^2}{n}}{n-1} \qquad (21)$$

where f_i is the mean dye concentration (frequency) at a distance X_i from the origin of the profile.

Two methods were employed to determine how well the observed concentration profiles defined a normal distribution. The normal

August 16 A.M., 1966

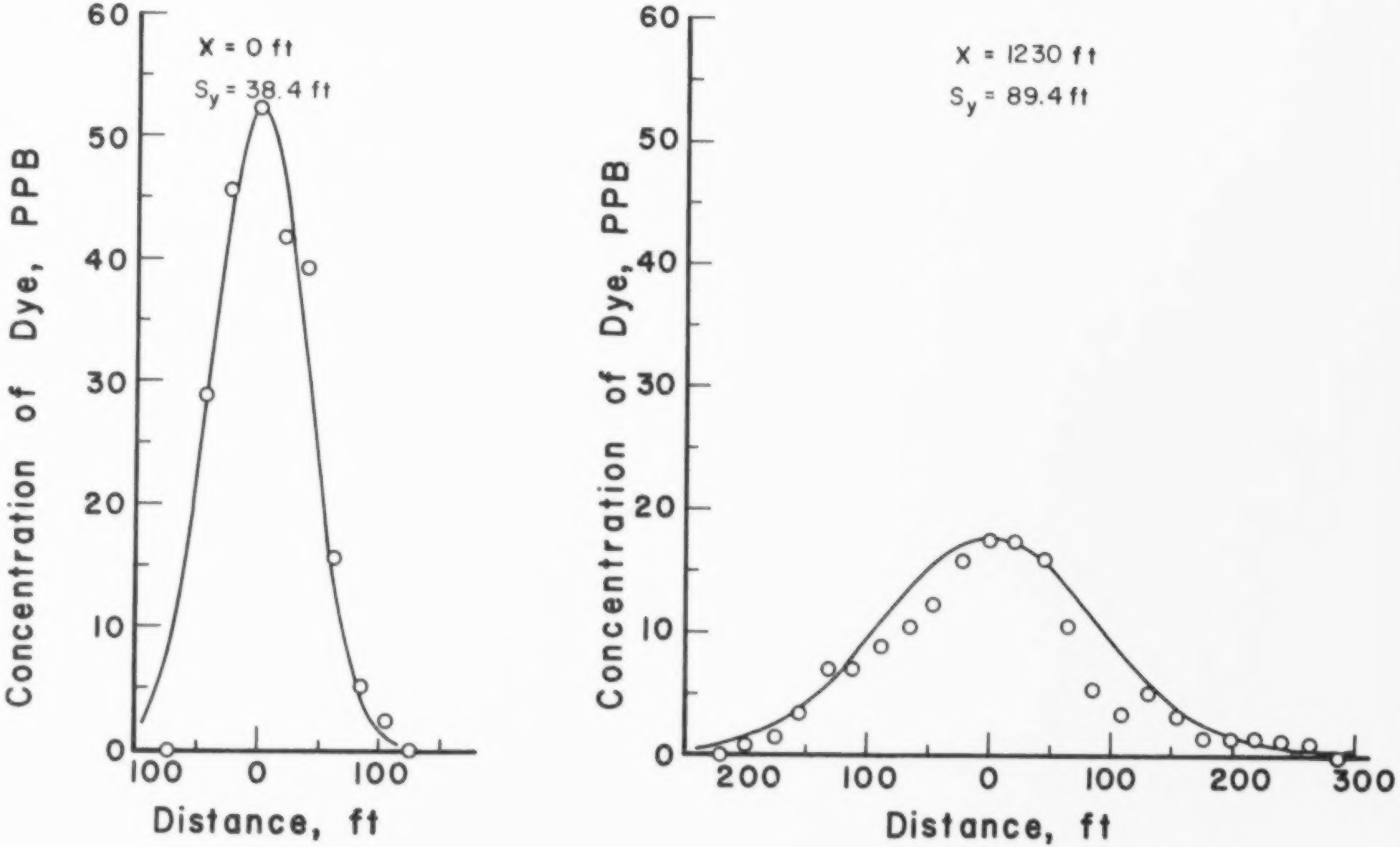


Fig. 15

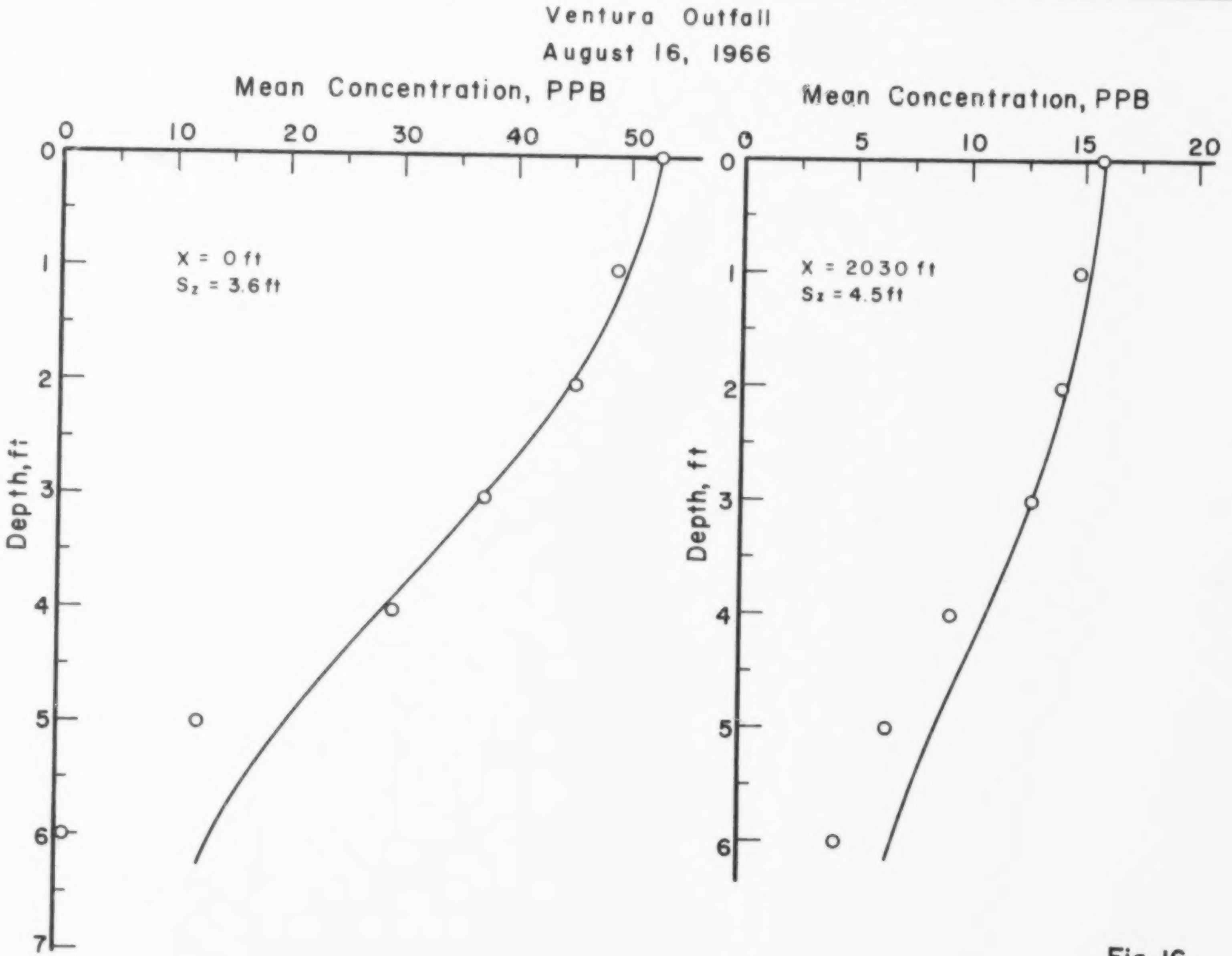

Ventura Outfall
August 16, 1966
Mean Concentration, PPB
0
10
20
30
40
50
Depth, ft
0
1
2
3
4
5
6
7
X = 0 ft
S_z = 3.6 ft
Mean Concentration, PPB
0
5
10
15
20
Depth, ft
0
1
2
3
4
5
6
X = 2030 ft
S_z = 4.5 ft

Fig. 16

curve can be defined by the equation

$$^{y}/y_0 = \exp - \frac{1}{2}\left(\frac{x}{\sigma}\right)^2 \tag{22}$$

where y is the dye concentration at a distance X from the peak concentration y_0 at the origin, and σ is the calculated standard deviation of the mean distribution. Curves calculated from equation (22) are also depicted in Figures 15 and 16 and show a reasonably good fit to the calculated distribution.

Another useful method of assessing the tendency of a given set of data to conform to a normal frequency distribution is by the use of probability paper. When normal probability paper is used, a normal cumulative frequency plots as a straight line, hence such plots are useful in evaluating the normality of a given set of observations. As mentioned previously, the spatial distribution of dye concentration is analogous to a frequency distribution; therefore, if the dye concentration is normally distributed the data should plot as a straight line on arithmetic-probability paper. For data like that shown in Figures 15 and 16 the probability scale represents the cumulative percentages of mean dye concentrations equal to or less than the calculated mean concentrations ($\bar{C}$) at a given distance in the vertical or cross plume directions. Mathematically the probability is given approximately as

$$p \doteq 100 \sum_{0}^{y,z} \bar{C}/n+1 \tag{23}$$

where $n = \sum_{0}^{y,z} \bar{C}$, the summation starting at the lateral extremity or water surface (Y = Z = 0) and extending over the width or depth of the dye plume.

Applying equation (23) to the data presented in Figures 15 and 16 gives the results shown in Figures 17 and 18. Except at the lateral boundaries, the data plot as straight lines.

Similar results were obtained in the experiments conducted on outfalls equipped with diffuser systems as evidenced by the results of an experiment conducted on the Santa Barbara Outfall depicted in Figures 19 and 20. In this case the calculated normal curves do not fit the observed mean dye concentration distributions as well as those shown in Figures 15 and 16. These results were partly due to the fact that in this experiment the mean dye concentrations were obtained from only two sampling runs; also, since a normal distribution has limits of $\pm\infty$, an "edge effect" or non-conformity between observed and theoretically predicted dye concentrations would be expected at the boundaries of the plume.

No mention has been made as yet of the lateral and vertical distribution of indicator bacteria. It is apparent that if a dispersion model is to be applicable to indicator bacteria, the distribution of microorganisms must conform to the assumed theoretical material distributions inherent in the derivation of the model. For the case in point the spatial distribution of mean coliform or other indicator bacteria density in the vertical and lateral coordinate directions of the waste plume should be similar to that of the dye concentration; and both should follow the Gaussian law. Several field experiments were conducted in which

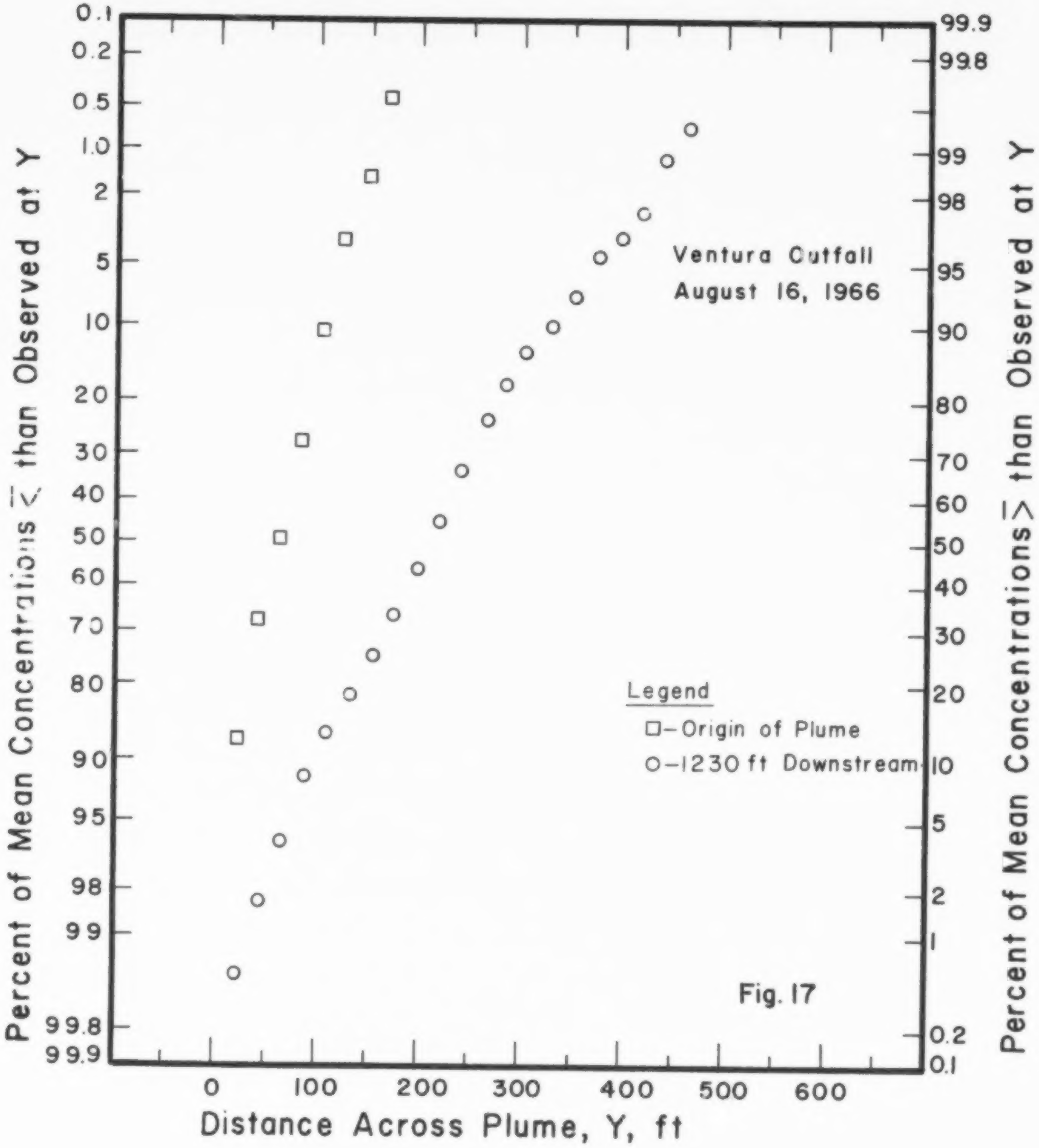

Percent of Mean Concentrations ≦ than Observed at Y
0.1
0.2
0.5
1.0
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
Percent of Mean Concentrations ≧ than Observed at Y
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.2
0.1
Ventura Outfall
August 16, 1966
Legend
□–Origin of Plume
○–1230 ft Downstream
0
100
200
300
400
500
600
Distance Across Plume, Y, ft

Fig. 17

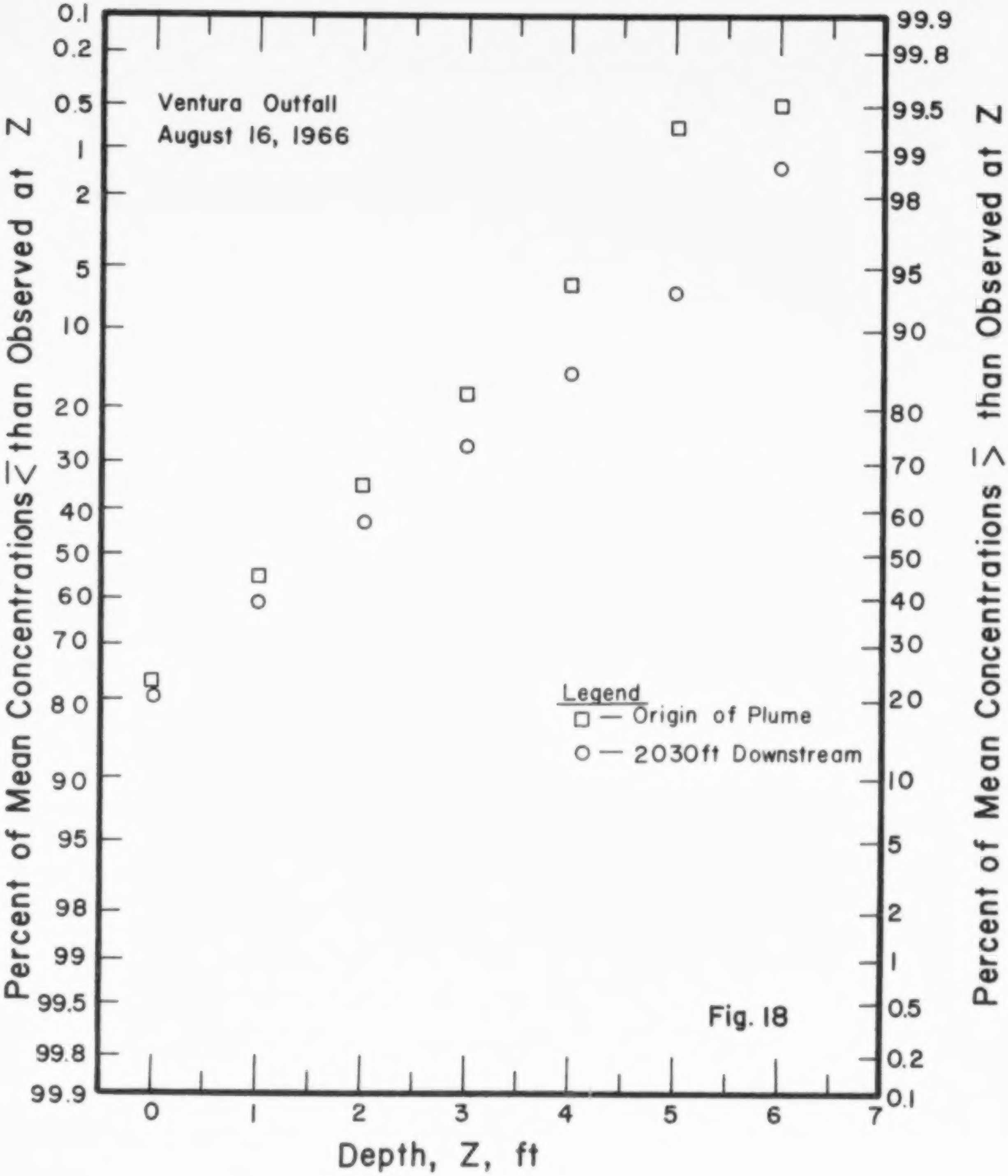

Ventura Outfall
August 16, 1966
Legend
□ — Origin of Plume
○ — 2030ft Downstream
Percent of Mean Concentrations ≤ than Observed at Z
Percent of Mean Concentrations ≥ than Observed at Z
Depth, Z, ft
0
1
2
3
4
5
6
7
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9

Fig. 18

Santa Barbara Outfall
March 18, 1966

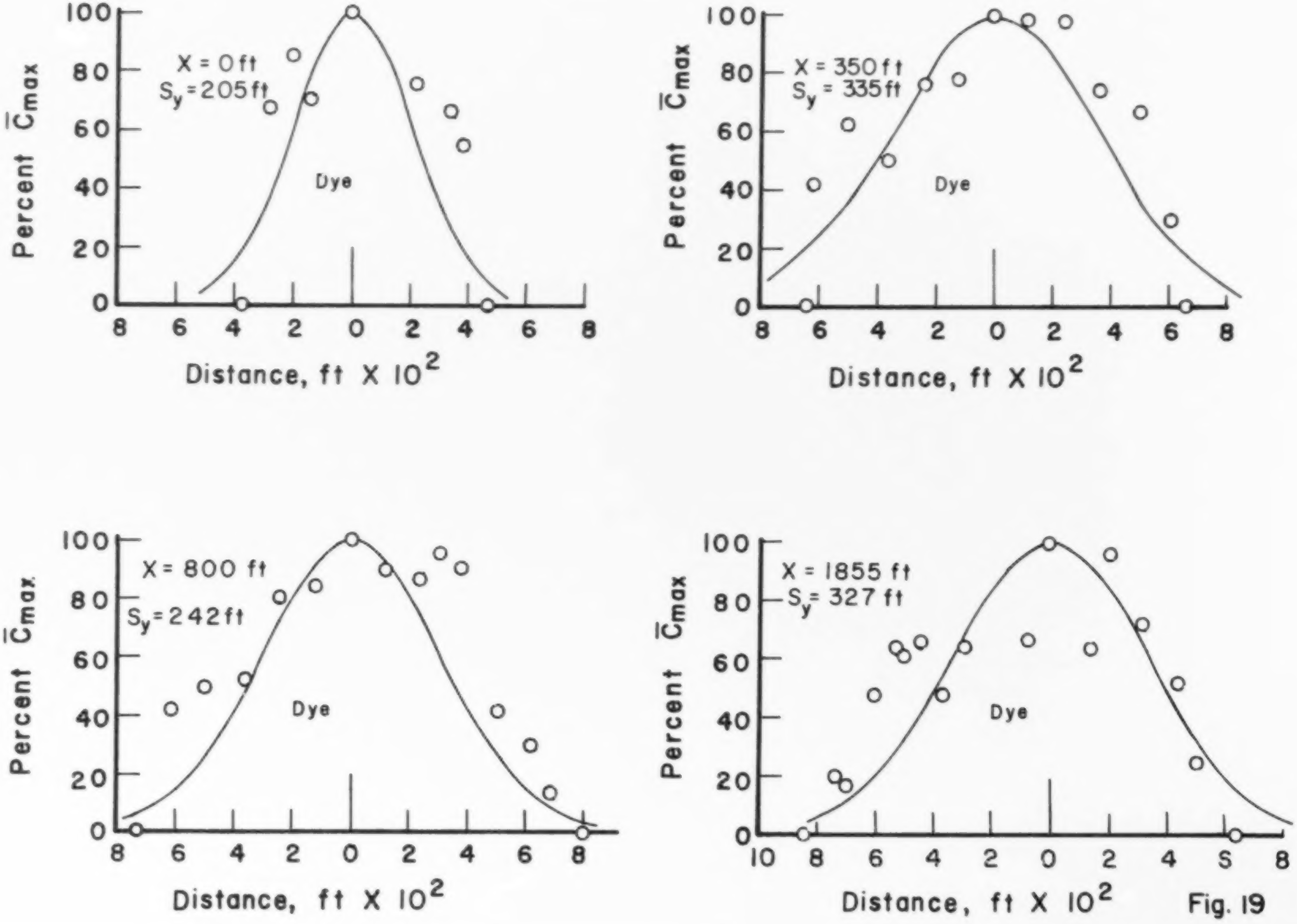
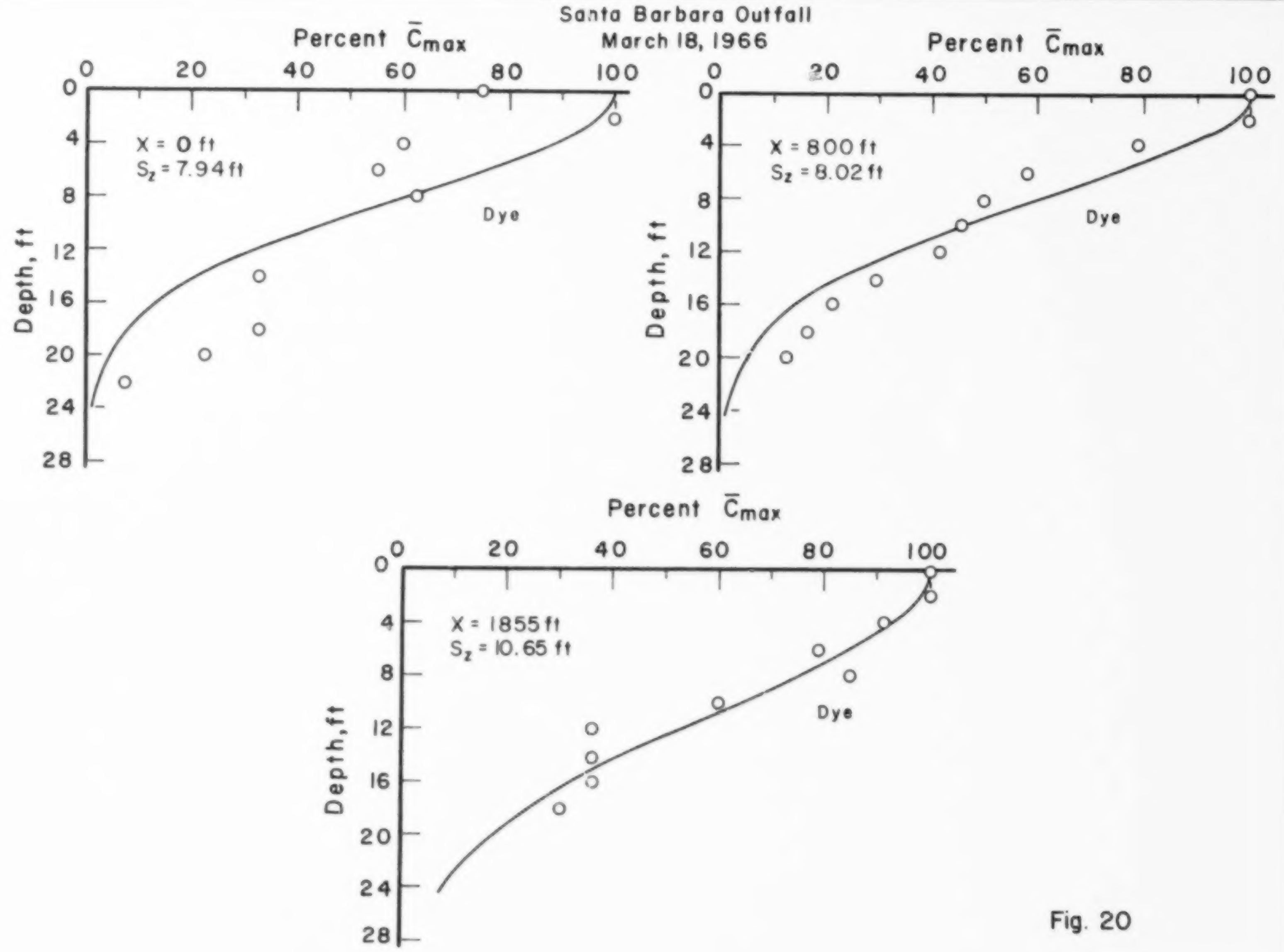


Fig. 19



Santa Barbara Outfall
March 18, 1966

Fig. 20

simultaneous measurements were made of coliform and dye concentrations in the vertical and lateral directions at selected points along the tagged waste plume. The partial results of one such experiment were shown previously in Figures 15 and 16. For purposes of comparison these data were plotted together with the corresponding data for the mean coliform density distributions as shown in Figures 21 and 22. It can be seen that in most instances the profiles of the two distributions are similar and approximately normal. Similar results were obtained in other experiments.

These results together with those presented by Csanady (1966) led to the conclusion that the basic assumption of a normal or Gaussian material distribution in the lateral and vertical directions of a steady waste plume is at least a good working rule yielding results which agree within practical engineering limits.

Application of Equations to Experimental Results

The data from the experiments conducted on November 11, 1966 at Ventura will be used to illustrate the applicability of the proposed dispersion equations. The results of this particular experiment were selected because they also illustrate the influence of the vertical component of diffusion on the overall dispersion phenomenon.

The calculated mean values of the diffusion parameters, $\sigma^2_{y,z}$ as functions of distance along the plume are shown in Figure 23. It is evident that in this particular experiment the lateral spread of the dye tracer at any point along the plume was approximately two orders of magnitude larger than that observed in the vertical direction.

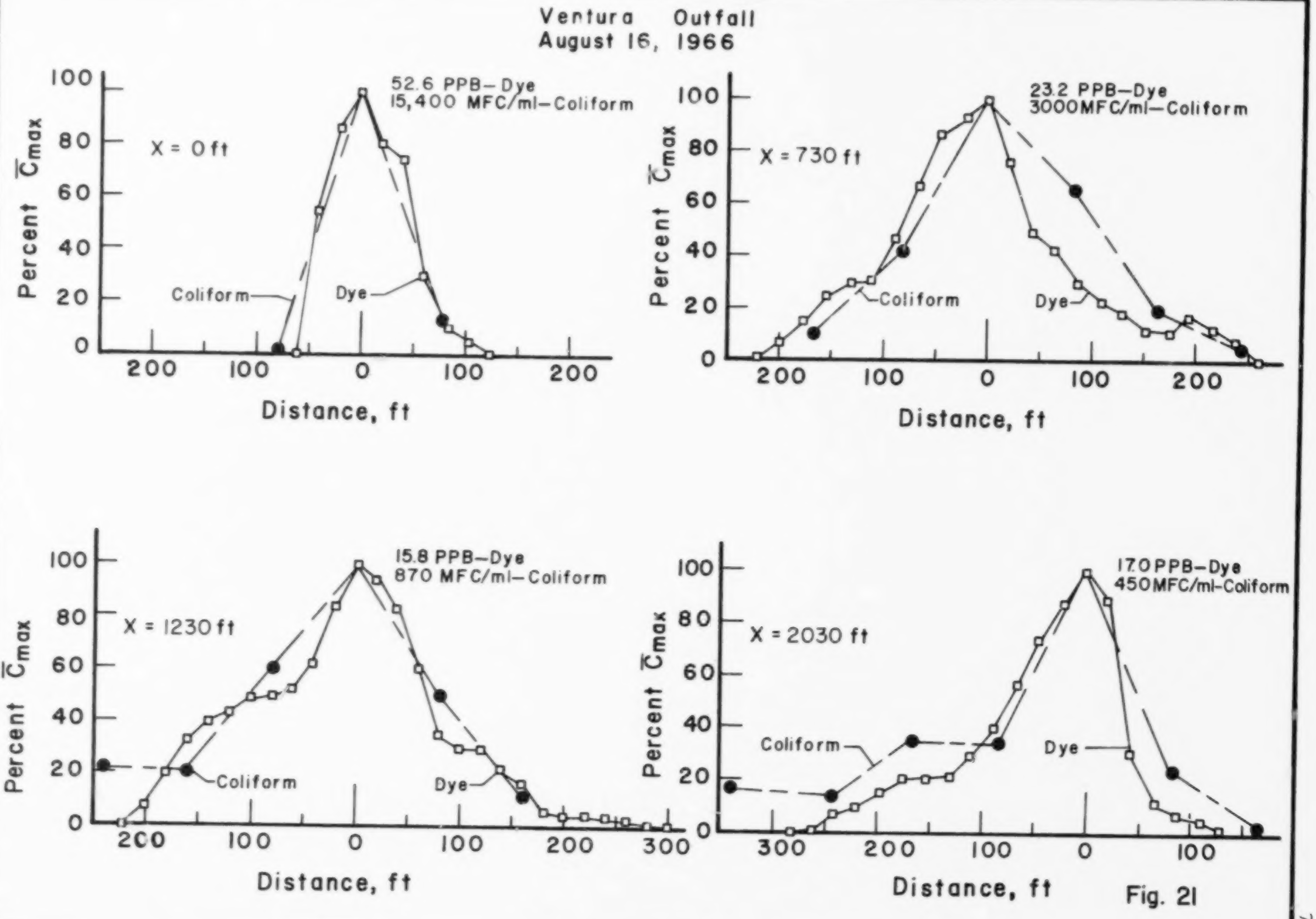

Ventura Outfall
August 16, 1966
X = 0 ft
52.6 PPB–Dye
15,400 MFC/ml–Coliform
X = 730 ft
23.2 PPB–Dye
3000 MFC/ml–Coliform
X = 1230 ft
15.8 PPB–Dye
870 MFC/ml–Coliform
X = 2030 ft
17.0 PPB–Dye
450 MFC/ml–Coliform
Coliform
Dye
Percent $\overline{C}_{max}$
Distance, ft
0
20
40
60
80
100
200
100
0
100
200
300

Fig. 21

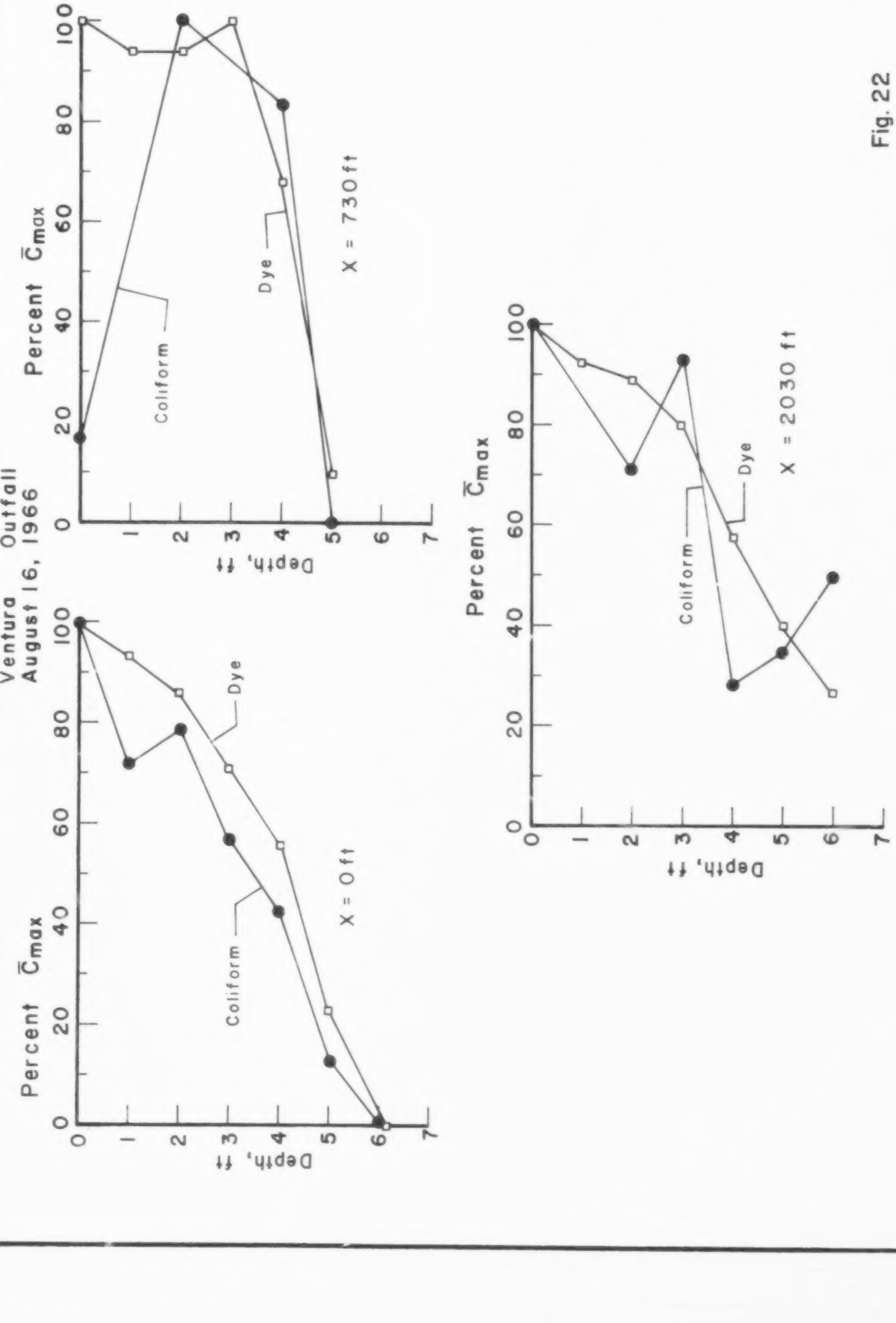

Ventura Outfall
August 16, 1966
Percent $\bar{C}_{max}$
0
20
40
60
80
100
Depth, ft
0
1
2
3
4
5
6
7
Coliform
Dye
X = 0 ft
X = 730 ft
X = 2030 ft

Fig. 22

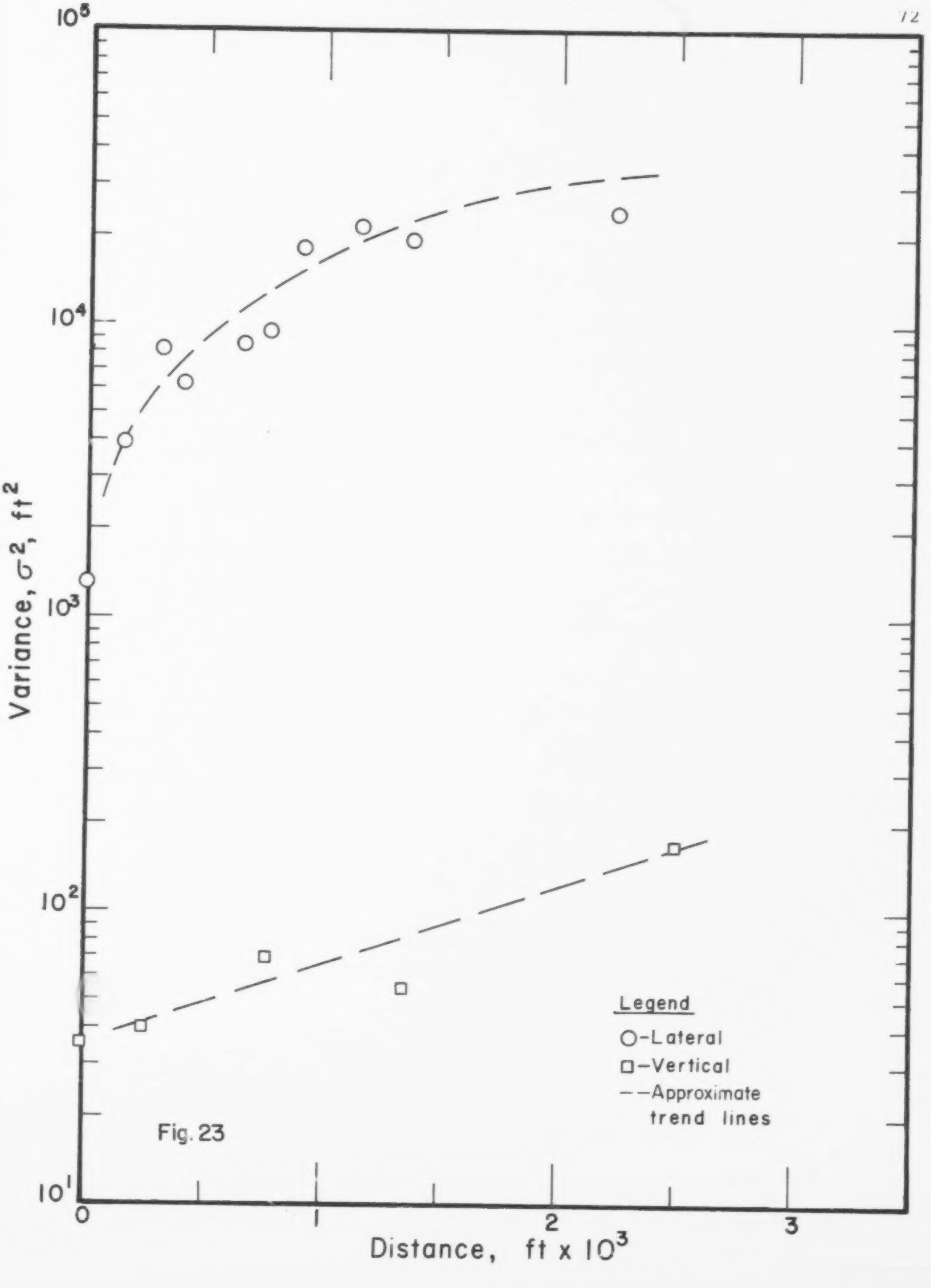

10⁵
10⁴
10³
10²
10¹
Variance, σ², ft²
0
1
2
3
Distance, ft x 10³
Legend
○-Lateral
□-Vertical
--Approximate trend lines

Fig. 23

At first glance these data appear to indicate that the vertical component of diffusion was negligible as compared to the horizontal component. It will be shown, however, that in this experiment vertical diffusion played a significant role in the observed physical dilution of the waste plume.

Values of the equivalent point-source variances, S^2, for this experiment were estimated from the observed values of σ^2 shown in Figure 23 together with equation (12). The results are presented in Figure 24 together with the calculated least squares trend lines. Statistical analyses of these data showed that the correlation coefficient, r, for the computed S^2_y-X relationship was 0.9135, which is significant at greater than the 0.1% confidence level (high correlation). The correlation for the S^2_z -X relationship was 0.8450 which for only four data points (two degrees of freedom), is significant at less than the 90% level indicating relatively poor correlation).

Applicability of Statistical Models

The applicability of the proposed dispersion models can best be assessed by comparing the solution of these equations for a given set of experimental conditions with the observed values of dye and bacteria concentrations.

Physical Dilution. Consider first the case of purely physical dilution of a waste plume. For the experiment discussed above we have from Tables 3, 6, and 7 and Figures 23 and 24

$Q = 2(10)^6$ gal/day

$C_p = 4$ppm

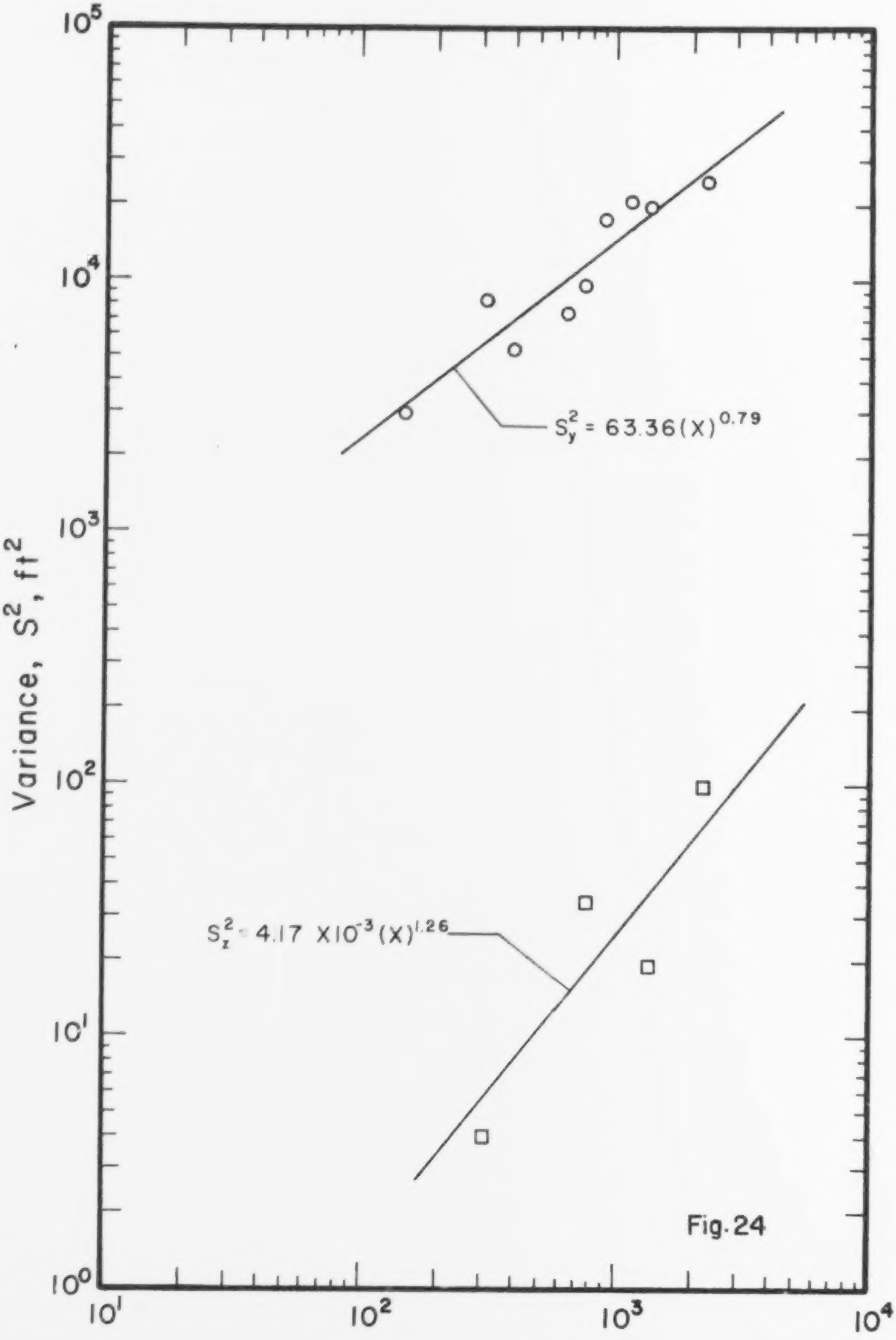

Variance, S^2, ft^2
Distance, ft
10^5
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
10^4
$S_y^2 = 63.36(X)^{0.79}$
$S_z^2 = 4.17 \times 10^{-3}(X)^{1.26}$

Fig. 24

Table 7

Summary of Diffusion Parameters

Number and Date of Study		Avg. Dye Concn. at Plant Cp (ppm)	Avg. Dye Concn. at Boil Co (PPB)	Initial Dilution Cp/Co x10^2	(dy/dt) (%/min)	D_y (ft^2/min)	D_z (ft^2/min)	σ_{yo} (ft x10^2)	σ_{zo} (ft)
1	1-27-66	3.00	24.2	1.24	-2.97	ND	ND	--	--
2	1-28-66	4.00	18.8	2.13	-0.78	ND	ND	--	--
3	3-17-66	3.00	73.1	0.41	-0.38	ND	ND	3.78	8.24
4	3-18-66	1.40	13.7	1.02	-1.00	345.00	1.44	2.07	7.91
5	5-13-66	ND	37.3	ND	-3.64	394.00	ND	1.63	8.94
6	6-10-66	3.00	89.5	0.34	-5.48	481.20	ND	1.00	4.69
7	8-15-66	3.15	116.0	0.27	-6.12	ND	ND	ND	10.01
8	8-16-66	3.00	124.5	0.24	-4.02	38.70	0.01	0.35	3.32
9	8-17-66	3.00	109.0	0.28	-6.35	69.90	0.05	1.44	3.51
10	11-10-66	2.60	34.0	0.77	-3.07	128.00	0.05	0.47	6.99
11	11-11-66	4.00	56.9	0.70	-2.56	83.60	0.04	0.36	6.00
12	2-23-67	4.00	90.8	0.44	-2.60	174.00	ND	0.42	8.10
13	2-24-67	4.00	40.2	1.00	-3.60	ND	ND	0.33	5.91
14	4-27-67	3.42	68.7	0.50	-7.53	26.30	1.32	0.27	14.50
15	4-28-67	3.48	37.1	0.94	-5.11	40.50	0.05	0.27	6.20
16	6-7-67	2.81	82.2	0.34	-0.37	123.00	0.51	0.50	22.51
17	6-8-67	2.81	51.0	0.55	-2.71	67.00	0.48	0.50	13.48
18	8-2AM-67	3.00	54.5	0.55	-5.40	304.00	ND	0.78	ND
19	8-2PM-67	3.00	61.7	0.49	-4.91	ND	ND	ND	10.50
20	8-3-67	3.00	41.5	0.72	-6.00	234.00	ND	0.72	5.91

Table 7 (cont.)
Summary of Diffusion Parameters

	Number and Date of Study	Avg.Dye Concn. at Plant Cp(ppm)	Avg.Dye Concn. at Boil Co(PPb)	Initial Dilution Cp/Co $\times 10^2$	(dy/dt) (%/min)	D_y (ft^2/min)	D_z (ft^2/min)	σ_{yo} (ft $\times 10^2$)	σ_{zo} (ft)
21	2-28-68	3.30	95.0	0.400	-7.27	112.50	ND	2.69	16.50
22	2-29-68	3.10	50.8	0.611	-0.81	ND	ND	3.95	5.91
23	3-20A-68	3.37	50.3	0.670	-1.97	ND	ND	ND	15.75
24	3-20B-68	3.37	50.3	0.669	-3.77	ND	ND	ND	15.75
25	3-21-68	3.10	53.9	0.575	-1.17	ND	ND	3.79	7.42
26	6-11A-68	2.91	32.3	0.895	-6.07	ND	ND	ND	4.89
27	6-11B-68	2.91	44.8	0.650	-7.66	171.52	8.08	0.51	ND
28	9-4-68	2.50	47.0	0.530	-1.92	87.14	1.16	0.11	7.71
29	9-5-68	2.26	30.3	0.750	-3.29	ND	ND	ND	ND
30	9-6-68	2.43	45.0	0.540	-2.36	ND	ND	ND	ND
31	10-30-68	2.71	56.6	0.480	-0.49	ND	2.06	1.20	26.2
32	10-31-68	2.84	50.5	0.560	-5.42	336.00	0.09	2.34	5.34
33	11-1AM-68	2.63	44.3	0.590	-9.97	ND	ND	1.57	ND
34	11-1PM-68	2.63	72.2	0.370	-0.34	ND	ND	2.89	ND
35	12-28-68	3.08	86.8	0.350	-3.55	ND	ND	4.51	ND
36	12-29-68	2.93	74.6	0.390	-6.84	3393.53	ND	4.94	11.85
37	2-20-69	1.69	57.2	0.300	-0.73	ND	ND	3.76	6.24
38	3-20AM-69	2.55	61.0	0.418	-9.46	ND	ND	ND	ND
39	3-20PM-69	2.55	123.5	0.210	0.00	693.35	ND	[illegible].58	16.43

$$C_0 = 0.057 \text{ ppm}$$

$$U = 16.2 \text{ ft/min}$$

$$\sigma_{y0} = 36 \text{ ft.}$$

$$\sigma_{z0} = 6 \text{ ft}$$

$$S_y^{\,2} = 63.4\ (x)^{0.79} \text{ ft}^2$$

$$S_z^{\,2} = 4.2\ (10)^{-3}\ (x)^{1.26} \text{ ft}^2$$

The estimated mean maximum dye concentration at the origin of the plume can be obtained from equation (15), that is

$$C_o = \frac{QC_p}{\pi U \sigma_{yo} \sigma_{zo}}$$

where C_p is the mean dye concentration in the treatment plant effluent. For the given conditions we find

$$C_0 = \frac{2(10)^6(8.33)(4)}{3.14(16.2)(36)(6)(1440)}$$

$$= 4.23(10)^{-6}\ {}^{10}/\text{ft}^3 = 0.066 \text{ ppm}$$

The calculated value of C_0 is in good agreement with the mean observed value of 0.057 ppm.

For purposes of comparison the distribution of maximum dye concentration along the plume centerline was estimated from both equation (16) and (17). The solutions of these equations are shown graphically in Figure 25 along with the best-fit trend line for the observed maximum concentration distribution. It is apparent that both equations yielded reasonably accurate estimates of mean maximum concentration up to a distance of about 1000 ft from the origin. Beyond this point equation (16) follows the trend line much closer than equation (17). These results reflect the fact that in this experiment vertical diffusion was a significant factor in the overall dilution of waste material. In other experiments, especially those in which the wind speed was relatively low and water column stability relatively high, vertical diffusion near the water surface was minimal. For these conditions it was found that both equations (16) and (17) yielded accurate and essentially identical estimates of the decrease in maximum dye concentration.

These results are in accord with those obtained by the Allan Hancock Foundation (1965) and Foxworthy (1968) in which it was found that vertical diffusion of dye patches and plumes becomes significant at mean wind speeds greater than about seven knots. The mean wind speed for the experiment under consideration was 10.6 knots.

Bacterial Disappearance. Next consider the case of combined dilution and die-away of coliform organisms. An estimate of the distribution of maximum concentration can be obtained by use of equations (19) and (20). Values of the die-away parameters a, K_1 and K_2 required in the solution of these equations are presented in Tables 5. It should be noted that the rate constants

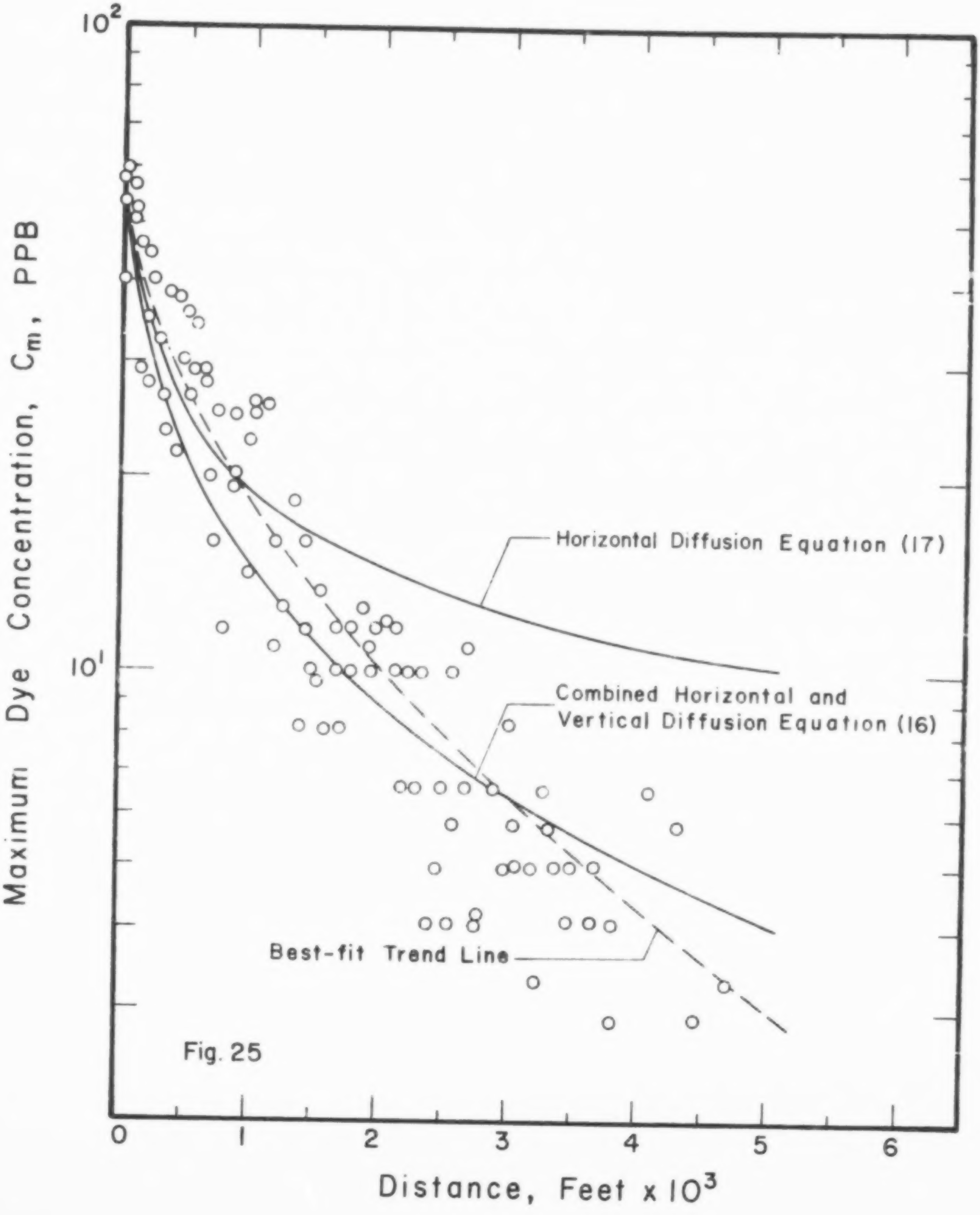

10^2
10^1
Maximum Dye Concentration, C_m, PPB
0
1
2
3
4
5
6
Distance, Feet x 10^3
Horizontal Diffusion Equation (17)
Combined Horizontal and Vertical Diffusion Equation (16)
Best-fit Trend Line

Fig. 25

given in this table are presented in units of minutes^{-1}. Conversion to units of distance^{-1} was accomplished by use of the relationship $k = K/U$, where U is the mean surface current speed in ft/min.

From Table 5 we have

$\underline{a} = 80.28\%$

$K_1 = 0.015 \text{ min}^{-1} = 0.00093 \text{ ft}^{-1} = k_1$

$K_2 = 0.10 \text{ min}^{-1} = 0.0062 \text{ ft}^{-2} = k_2$

$C_p = 9\ (10)^5$ MFC/ml $= 3.4\ (10)^9$ MFC/gal

$C_0 = 4.2 \times 10^3$ MFC/ml

The predicted mean initial coliform concentration can again be obtained from equation (15) using C_p, the observed coliform concentration at the treatment plant, and Q, $_{y0}$, and $_0$ as given in the previous example. Thus

$$C_0 = \frac{(3.4)(10)^9\ (2)(10)^6}{(3.14)(16.2)(36)(6)(1440)}$$

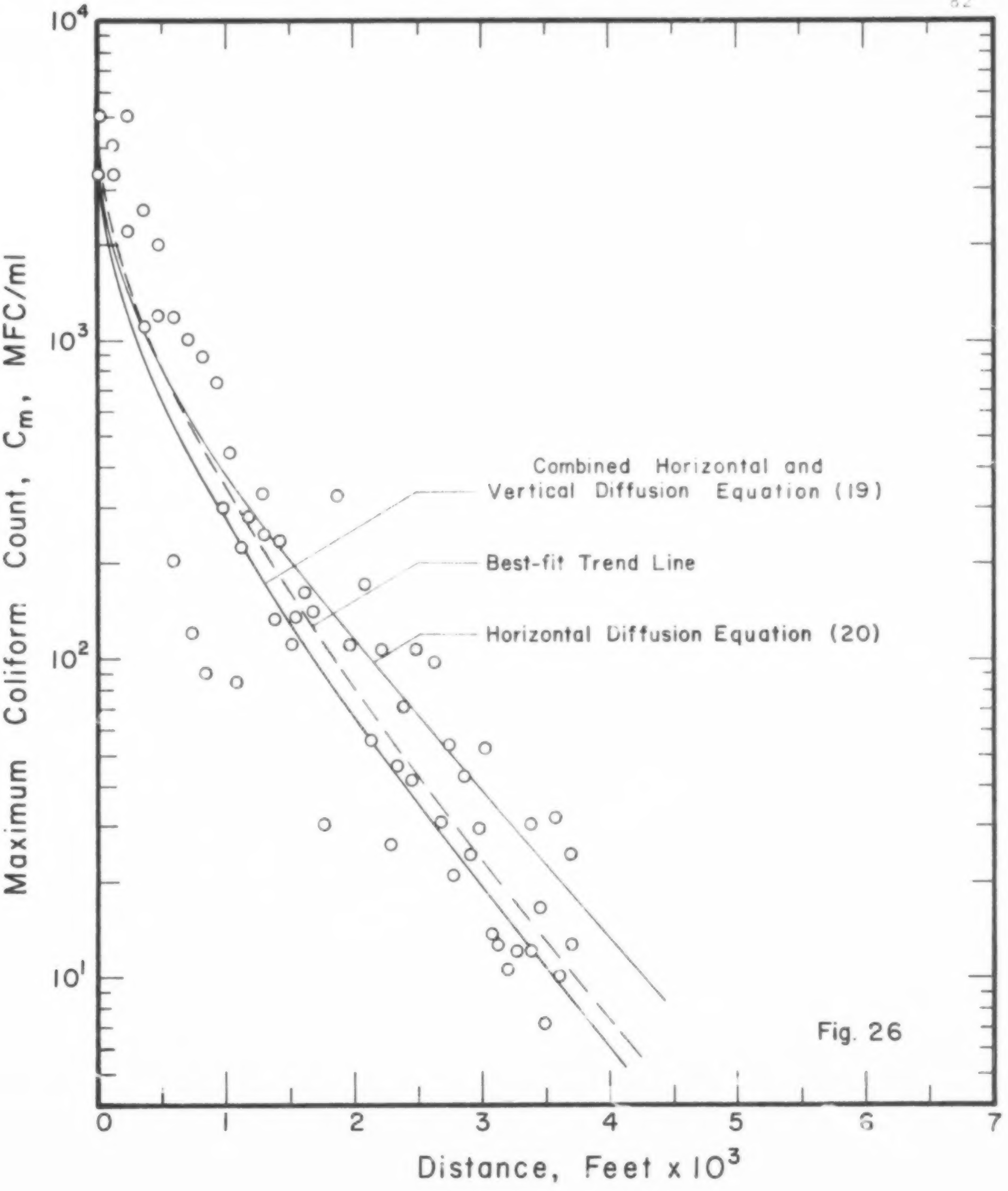
$$= 4.3\ (10)^8 \text{ MFC/ft}^3$$

$$= 1.52\ (10)^4 \text{ MFC/ml}$$

The calculated value of C_0 turns out to be approximately three times the observed mean value of $4.2\ (10)^3$ MFC/ml. This discrepency is due mainly to the fact that an insufficient number of samples (2) were taken to establish a statistically meaningful mean bacterial density at the treatment plant. On the other hand the mean observed value of C_0 was obtained from a series of ten samples taken at different times during the course of the experiment. Consequently the mean observed concentration was used to assess the applicability of equations (19) and (20) rather than calculated from equation (15). The results are shown graphically in Figure 26 together with the best fit trend line for the observed distribution of maximum concentration. These results are similar to those obtained above for physical dilution of the plume. It is apparent that in this experiment the proposed model for combined two-dimensional diffusion and die-away of coliform bacteria yielded the most accurate prediction of the observed mean concentration distribution.

It is important to note that the close agreement between observed and predicted concentration distributions shown in Figures 25 and 26 was not typical of all experiments. In some cases, especially where insufficient data were collected to adequately define the relevant dispersion parameters, the agreement was in fact poor. However, sufficient good quality field data were collected from which to conclude that the proposed dispersion models form a satisfactory basis for engineering estimates of dilution and bacterial die-away in surface waste plumes.

It is also worth noting that if the ordinates of the curves representing equation (19) in Figure 26 are multiplied by a factor of about two, the result closely approximates the distribution of "peak" coliform concentration. The same is true for the distribution of maximum dye concentration shown in Figure 25.



10^4
10^3
10^2
10^1
Maximum Coliform Count, C_m, MFC/ml
0
1
2
3
4
5
6
7
Distance, Feet x 10^3
Combined Horizontal and Vertical Diffusion Equation (19)
Best-fit Trend Line
Horizontal Diffusion Equation (20)

Fig. 26

This observation is important, as mentioned earlier, since it gives support to Csanady's (1966) experimental findings that the "peak" concentration in continuous dye plumes was about twice the maximum mean concentration. The appropriate dispersion model for the distribution of "peak" bacterial concentration in a steady waste plume can be obtained, for example, by multiplying equations (19) and (20) by a factor of about two.

Discussion. One of the principal aims of the previous development was to illustrate the applicability of dispersion models which incorporate the terms $(S^2 + \sigma_0^2)$ as the basic diffusion parameters. Models such as this are particularly valuable since they can be employed to estimate the physical dilution of waste material discharged from a source of any assumed initial size; providing, of course, the initial concentration distributions are Gaussian. In order to apply the proposed equations to a particular situation one must obtain, either from actual field experiments or the work of others, relevant relationships between the coordinate point-source variances and dispersion time (or distance). The necessary experimental data are relatively easy to acquire by the methods described herein and by Csanady (1966). In the absence of such information it is necessary to rely on data presented by other investigators. The problem here lies in the fact that data collected in the same or different oceanic areas are strongly influenced by variable environmental conditions. Hence the direct application of data collected in a "foreign" environment to a particular local situation may prove hazardous. To illustrate this point let us consider the data collected by the Allan Hancock Foundation (1965) and

Foxworthy (1968) in a series of dye patch experiments conducted off the coast of southern California. These experiments were carried out inside and outside of continuous waste plumes dispersing at the ocean surface. The results of these studies were interpreted in terms of observed S^2 vs. $\underline{t}$ relationships for the longitudinal, lateral, and vertical axes of the dye patches. These data are presented graphically on double log paper as shown in Figures 27 through 29. The best-fit regression lines shown in these figures were based on an assumed linear relationship between the variables over the indicated period of observation. In each diagram there is a strong trend for S^2 to increase with diffusion time as evidenced by the highly significant correlation coefficients obtained for these data. However, it is also evident that there is considerable scatter of the plotted points about the indicated trend lines. This is due, at least in part, to the large variety of oceanographic conditions encountered in these experiments. The rate of vertical and horizontal diffusion near the water surface is known to be a function of such factors as wind speed, water column stability, current shear, and the rate of energy dissipation. Since these factors varied significantly from study to study, a variable S^2 at a given diffusion time was to be expected.

Results similar to those presented in Figures 27 through 29 were obtained by Okubo (1968) for horizontal diffusion in the ocean. He presented a series of diffusion diagrams, composed of data collected from various sources,which illustrated the ${S_r}^2$ vs. $\underline{t}$ relationship for a time scale ranging from around one hour to one year. In his analysis ${S_r}^2$ is the variance of an equivalent circular patch of

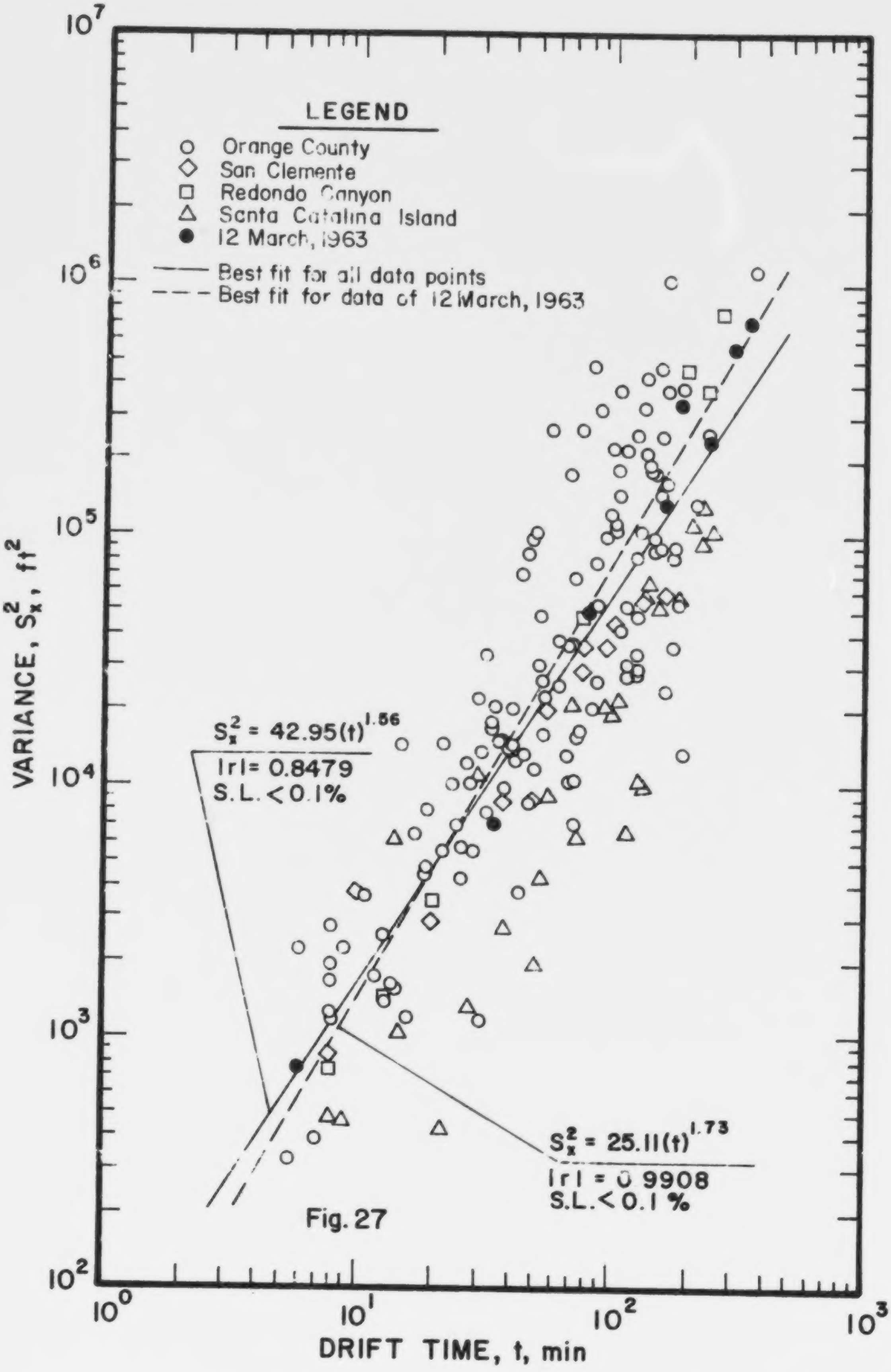

LEGEND
○ Orange County
◇ San Clemente
□ Redondo Canyon
△ Santa Catalina Island
● 12 March, 1963
—— Best fit for all data points
– – – Best fit for data of 12 March, 1963
$S_x^2 = 42.95(t)^{1.56}$
$|r| = 0.8479$
S.L. < 0.1%
$S_x^2 = 25.11(t)^{1.73}$
$|r| = 0.9908$
S.L. < 0.1 %
VARIANCE, S_x^2, ft^2
10^2
10^3
10^4
10^5
10^6
10^7
DRIFT TIME, t, min
10^0
10^1
10^2
10^3

Fig. 27

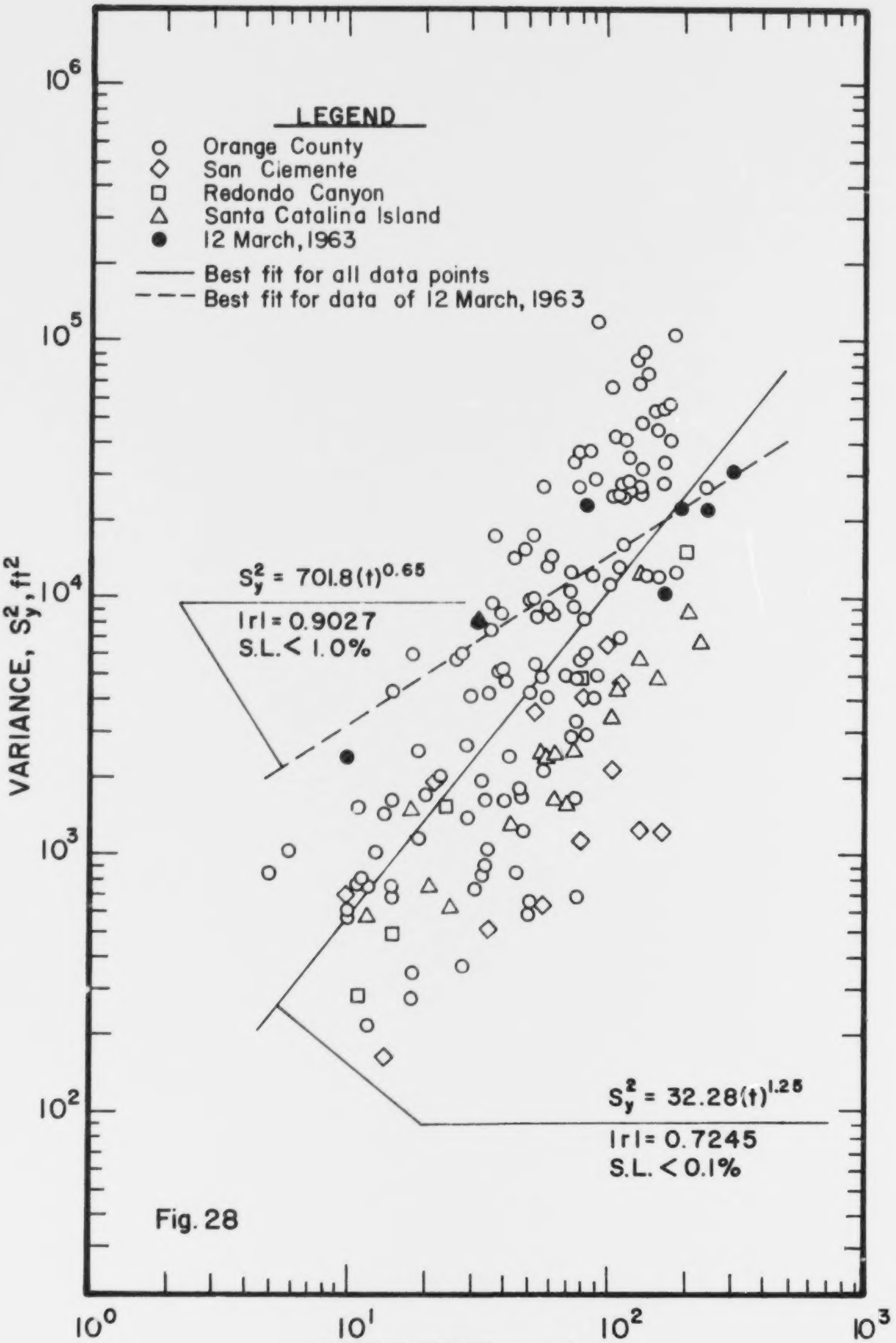

LEGEND
○ Orange County
◇ San Clemente
□ Redondo Canyon
△ Santa Catalina Island
● 12 March, 1963
—— Best fit for all data points
– – Best fit for data of 12 March, 1963
$S_y^2 = 701.8(t)^{0.65}$
|r| = 0.9027
S.L. < 1.0%
$S_y^2 = 32.28(t)^{1.25}$
|r| = 0.7245
S.L. < 0.1%
10^6
10^5
10^4
10^3
10^2
VARIANCE, S_y^2, ft^2
10^0
10^1
10^2
10^3
DRIFT TIME, t, min

Fig. 28

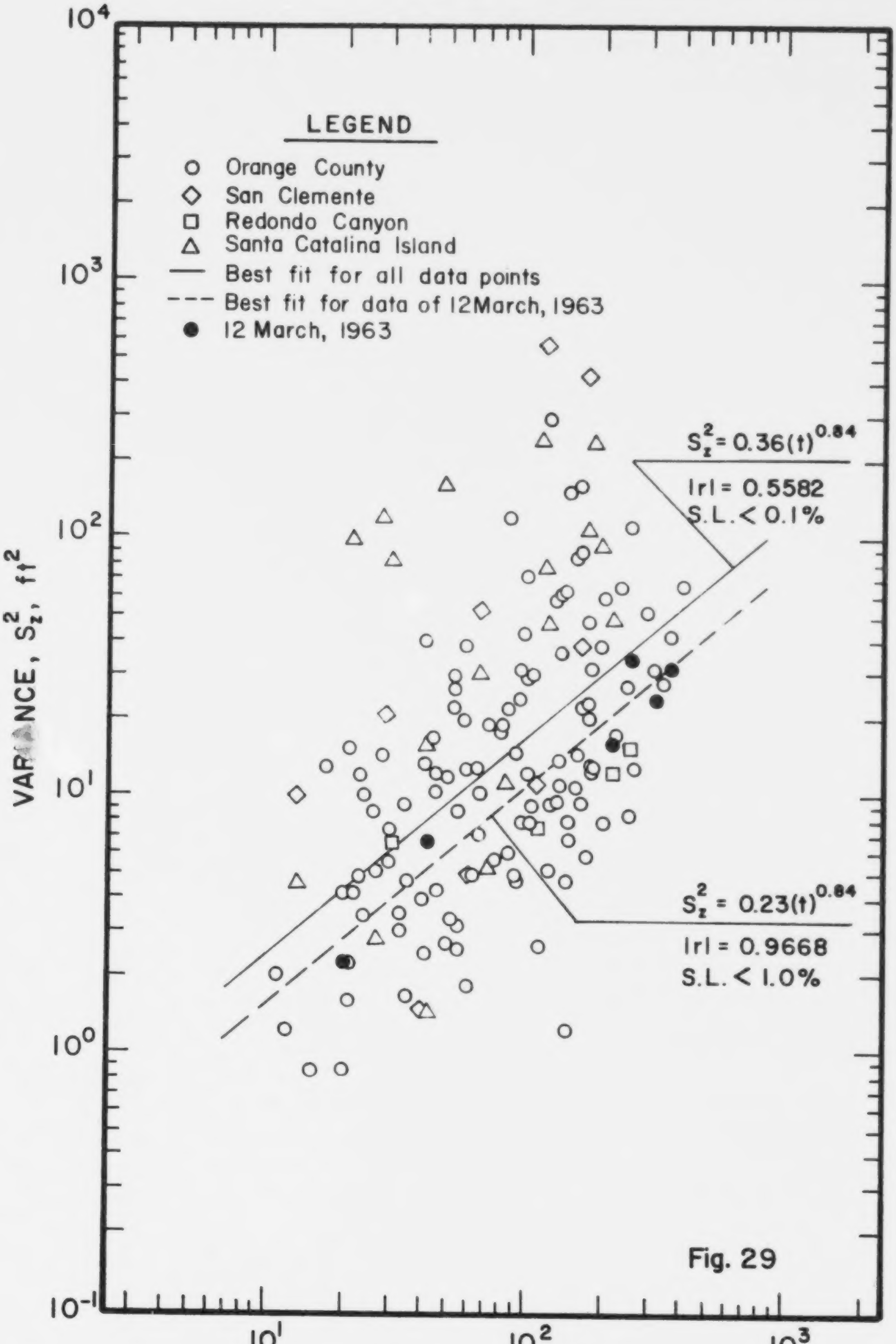

LEGEND
○ Orange County
◇ San Clemente
□ Redondo Canyon
△ Santa Catalina Island
— Best fit for all data points
--- Best fit for data of 12March, 1963
● 12 March, 1963
$S_z^2 = 0.36(t)^{0.84}$
$|r| = 0.5582$
S.L. < 0.1%
$S_z^2 = 0.23(t)^{0.84}$
$|r| = 0.9668$
S.L. < 1.0%
10^4
10^3
10^2
10^1
10^0
10^{-1}
VARIANCE, S_z^2, ft^2
10^1
10^2
10^3
DRIFT TIME, t, min

Fig. 29

material rather than the variance in a particular coordinate direction. Okubo concluded that although there was considerable scatter of his data, the calculated trend lines, showing S_r^2 to increase with t to a power of from two to three, could be used to predict the rate of horizontal diffusion in the ocean. The fact that S_r^2 did not vary linearly with t was interpreted by Okubo to mean that the so-called Fickian law of diffusion does not apply to the horizontal spread of material in the ocean.

Similar conclusions could be drawn for the limited data shown in Figures 27 through 29. It is important to note, however, that the trend line for the lateral and vertical variances in these experiments varied with t to a power between one and two. It was observed that in many of the individual experiments S_y^2 and S_z^2 varied with t to a power not significantly different from one. This point is illustrated here by the results of one typical experiment shown as solid circles in Figure 28 and 29. It appears, therefore, that lateral and vertical diffusion-- which are of prime importance in the net dispersion of continuous plumes-- may actually follow the Fickian law as modified by local environmental conditions.

Obviously further research is needed to verify this hypothesis and to establish the influence of environmental factors on oceanic diffusion. Some work has been done with regard to diffusivity coefficients and the environment [see, for example, Foxworthy (1968)]; however more work pertaining to S^2 vs. t relationships is needed.

Until further information is obtained diffusion diagrams such as those presented herein and by Okubo may be used to make no less than rough predictions of diffusion in the ocean.

The problems involved in predicting relevant parameters for use in the proposed bacterial die-away equations are discussed in a later section of this report.

Diffusivity Coefficients

It has become more or less traditional in the design of waste outfall systems to use dispersion models derived from the basic differential equation of continuity. Models of this type are usually written in terms of one-, two- or three-dimensional diffusivity coefficients as the basic diffusion parameters.

The statistical models previously discussed in this report can be expressed, for certain limiting conditions, in terms of so-called "apparent" or "effective" diffusivity coefficients defined by the equation

$$D = \frac{1}{2} \frac{dS^2}{dt} \tag{24}$$

where the point-source variance in a given coordinate direction, S^2, is a function of time. The terms "apparent" and "effective" are used here to indicate that the diffusion of material is brought about by combined molecular and eddy motion, current shear, etc.

For the case of diffusion in a steady current $t = {}^x/u$, which, when substituted into equation (24) gives

$$D = \frac{U}{2} \frac{dS^2}{dx} \tag{25}$$

here S^2 is a function of distance. The coefficients thus defined are variable unless the so-called asymptotic or linear diffusion phase has been reached, i.e., when $S^2 \propto X$ (or t). Under such considitons values of the coefficients can be obtained by integrating equations (24) and (25) between appropriate limits. Thus

$$D\int_0^1 dx \doteq \frac{U}{2}\int_0^1 ds^2 \tag{26}$$
$$\doteq \frac{U}{2}\left(\frac{S_1^2 - S_0^2}{X_1 - X_0}\right)$$

Since $S_0^2 \rightarrow 0$ for a point-source, equation (26) reduces to

$$D \doteq \frac{US^2}{2X} \tag{27}$$

The equivalent expression for a large-scale plume is

$$D \doteq \frac{U}{2}\left(\frac{\sigma_1^2 - \sigma_0^2}{X_1 - X_0}\right) \tag{28}$$

Substituting the relationship for the variance of an equivalent point-source given by equation (12) into (28) yields an equation identical to (27).

In the event the asymptotic diffusion phase has not been reached, equations (26) and (27) yield an average diffusivity coefficient for the period of observation.

Deterministic Models

The proposed volume source equations can be written in terms of constant diffusivity coefficients by simply substituting coordinate values of $\frac{2DX}{U}$ or 2Dt for the appropriate values of S^2. For example, in the case of combined horizontal and vertical diffusion of a conservative waste we have from equations (17) and (16)

$$C_m = \frac{C_o}{\left[\dfrac{2D_y X}{U\sigma_{yo}^2}+1\right]^{1/2}\left[\dfrac{2D_z X}{U\sigma_{zo}^2}+1\right]^{1/2}} \tag{29}$$

where C_0 is given by equation (15).

For one-dimensional horizontal diffusion we obtain

$$C_m = \frac{C_o}{\left[\dfrac{2D_y X}{U\sigma_{yo}^2}+1\right]^{1/2}} \tag{30}$$

The corresponding equations for the dispersion of indicator bacteria can be obtained by multiplying equations (29) and (30) by equation (3) for bacterial die-away, thus

$$C_m = \frac{C_o}{\left[\dfrac{2D_y X}{U\sigma_{yo}^2}+1\right]^{1/2}\left[\dfrac{2D_z X}{U\sigma_{zo}^2}+1\right]^{1/2}}\left[a e^{-k_1 x} + (100-a) e^{-k_2 x}\right] \tag{31}$$

and

$$C_m = \frac{C_o}{\left[\dfrac{2D_y X}{U\sigma_{yo}^2}+1\right]^{1/2}}\left[a e^{-k_1 x} + (100-a) e^{-k_2 x}\right] \tag{32}$$

Applicability of Deterministic Models. As mentioned previously, in the majority of the present experiments the variances, S^2, of the lateral and vertical dye distributions were observed to vary linearly with time (or distance). Hence the spread of dye in these coordinate directions can be described by Fickian-type equations involving constant diffusivity relationships. This implies that equations (29) through (32) are directly applicable to these experimental results.

Physical Dilution. Using the data presented above for the experiment of November 11, 1966 off Ventura and the information given in Table 7, that is

$$D_y = 83.6 \text{ ft}^2/\text{sec}$$
$$D_z = .0432 \text{ ft}^2/\text{sec}$$

we can solve equations (29) and (30). The solutions of these equations are shown in Figure 30 together with the best-fit trend line for maximum dye concentration. It is evident that equation (29) yields the most accurate estimate of the observed concentration distribution. As in the previous example the vertical component of diffusion was significant because of the relatively high wind speed encountered during this study. As will be discussed later, D_z was found to increase with increasing wind speeds, becoming significant at wind speeds greater than around 7 knots.

Bacterial Disappearance. The solutions of equations (31) and (32) for the predicted decrease in maximum coliform concentration are shown in Figure 31. Comparing the predicted decline with the trend line for the observed concentrations indicates that equation (31) yields a very accurate estimate of observed mean coliform

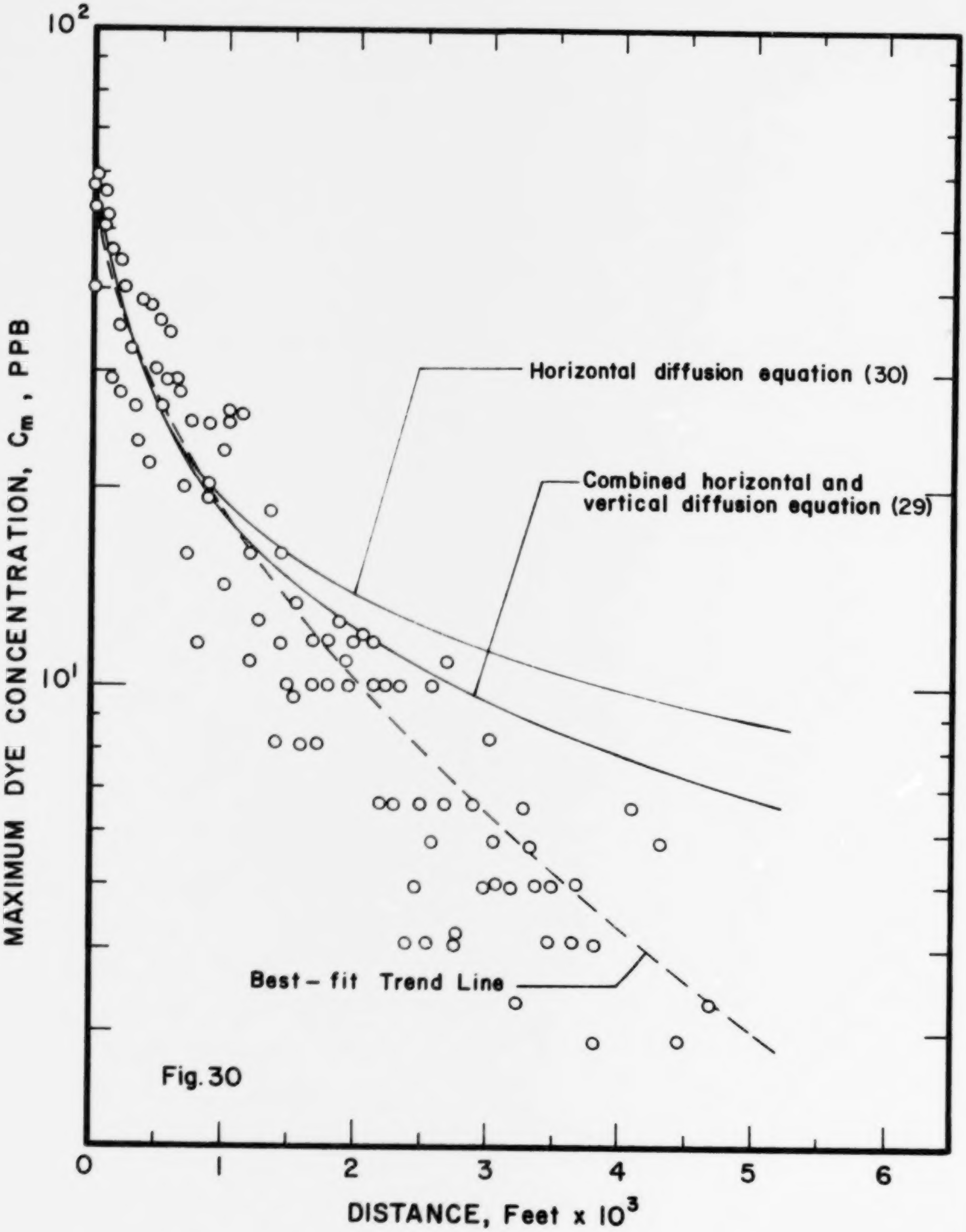
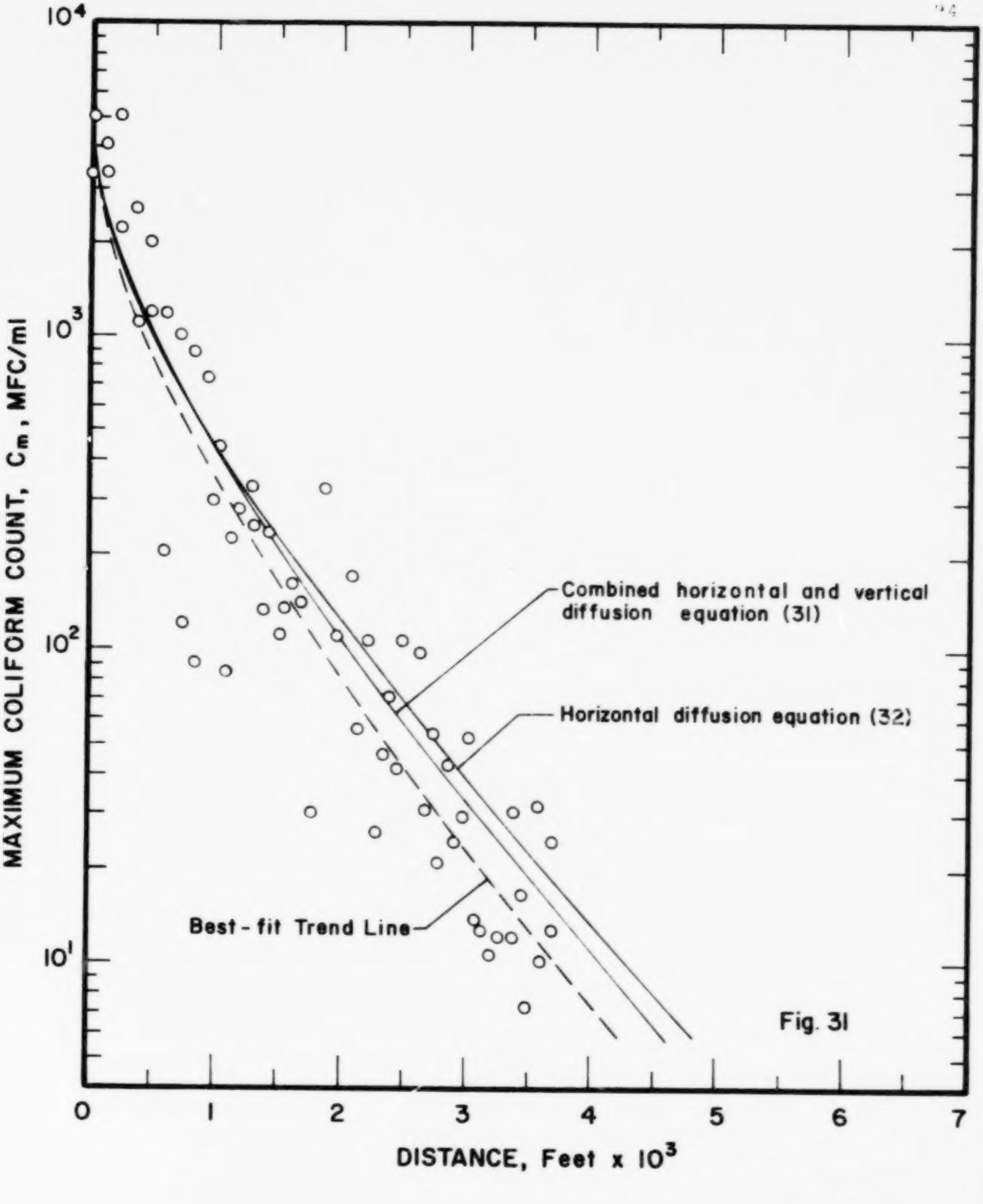

10²
10¹
MAXIMUM DYE CONCENTRATION, C_m , PPB
Horizontal diffusion equation (30)
Combined horizontal and vertical diffusion equation (29)
Best - fit Trend Line
0
1
2
3
4
5
6
DISTANCE, Feet x 10³

Fig. 30



10^4
10^3
10^2
10^1
MAXIMUM COLIFORM COUNT, C_m, MFC/ml
0
1
2
3
4
5
6
7
DISTANCE, Feet x 10^3
Combined horizontal and vertical diffusion equation (31)
Horizontal diffusion equation (32)
Best-fit Trend Line

Fig. 31

distribution. These results are also similar to those obtained from application of the statistical models.

Discussion. Both the statistical and deterministic models of oceanic dispersion appear to yield satisfactory estimates of the decrease in maximum dye and coliform concentrations. The choice of which model to use depends, to a great extent, on how well the diffusion parameters can be predicted for a given set of environmental conditions. The problems involved in interpreting individual and grouped data describing horizontal and vertical S^2 vs. t relationships were discussed earlier. On the other hand information on diffusivity coefficients in the ocean is more abundant and the problems involved in predicting relevant values are not as severe. In the case of the present studies it was possible to determine approximate diffusivity coefficients by use of equations (27) and (28). Although D_y and D_z were found to be essentially constant for most of the experiments, the magnitude of these coefficients varied considerably from study to study. Such variations were noted by many investigators in the past and led eventually to the proposal that the coefficients of diffusivity were proportional to some measure of the scale of the diffusion phenomenon. In the present experiments it was found that the horizontal coefficients are related to the initial size, taken as S_{yo} and σ_{yo}, for the small-scale dye patches and large-scale plumes. The relationship is shown in Figure 32 in which the diffusivity coefficients are plotted against the initial standard deviations of the observed concentration distributions. Although there is considerable scatter of the plotted points about the linear best-fit line, the correlation

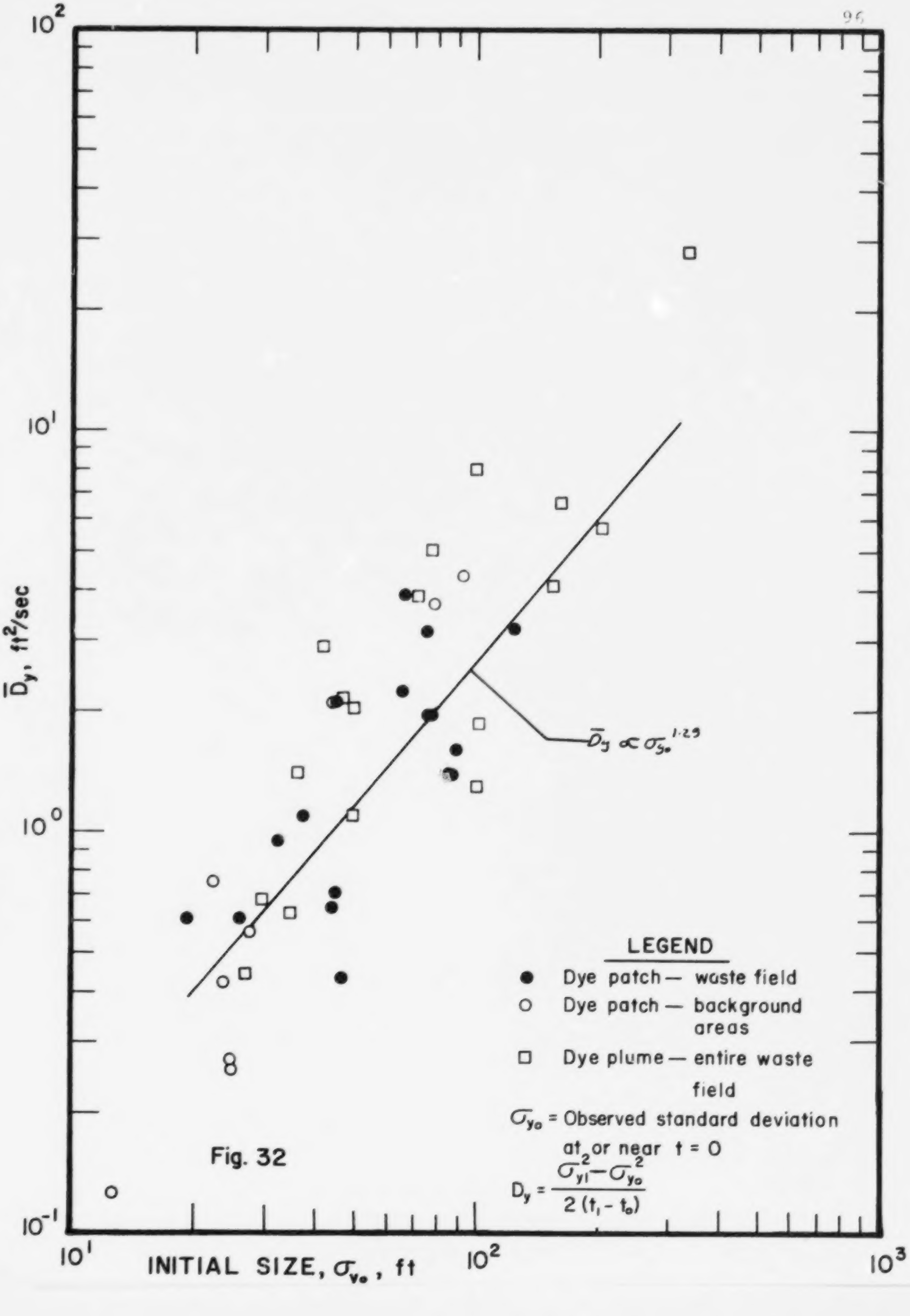

10^2
10^1
10^0
10^{-1}
$\overline{D}_y$, ft²/sec
10^1
10^2
10^3
INITIAL SIZE, σ_{y_o}, ft
$\overline{D}_y \propto \sigma_{y_o}^{1.29}$
LEGEND
● Dye patch — waste field
○ Dye patch — background areas
□ Dye plume — entire waste field
σ_{y_o} = Observed standard deviation at or near t = 0
$D_y = \frac{\sigma_{y1}^2 - \sigma_{y_o}^2}{2(t_1 - t_o)}$

Fig. 32

coefficient for these data is 0 8581 which is significant at greater than the 0.1% confidence level. It is interesting to note that the empirical relationship shown in Figure 32 is very similar to that suggested by Richardson (1926) for the so-called coefficient of neighbor diffusivity and initial neighbor separation.

Regarding the vertical coefficient of diffusivity, no relationship could be established between D_z and the size of the dye patches and plumes. As mentioned previously, Foxworthy (1968) presented experimental evidence which indicated that the rate of vertical diffusion near the ocean surface is influenced more by mean wind speed than any other single environmental factor. The relationship between these variables for the present experiments is shown in Figure 33. The correlation coefficient for the best fit line is $\underline{r} = 0.7816$ which is significant at the 0.1% confidence level. The values of D_z depicted in the figure were computed from equations (27) and (28) and, as in the case of the lateral coefficients, individual values of D_z were found to be nearly constant in most of the experiments.

The relationships shown in Figures 32 and 33 provide a practical means of estimating diffusivity coefficients for use in the proposed or similar Fickian-type dispersion models. In this respect these diagrams should prove valuable in the design of future near-shore waste outfall systems.

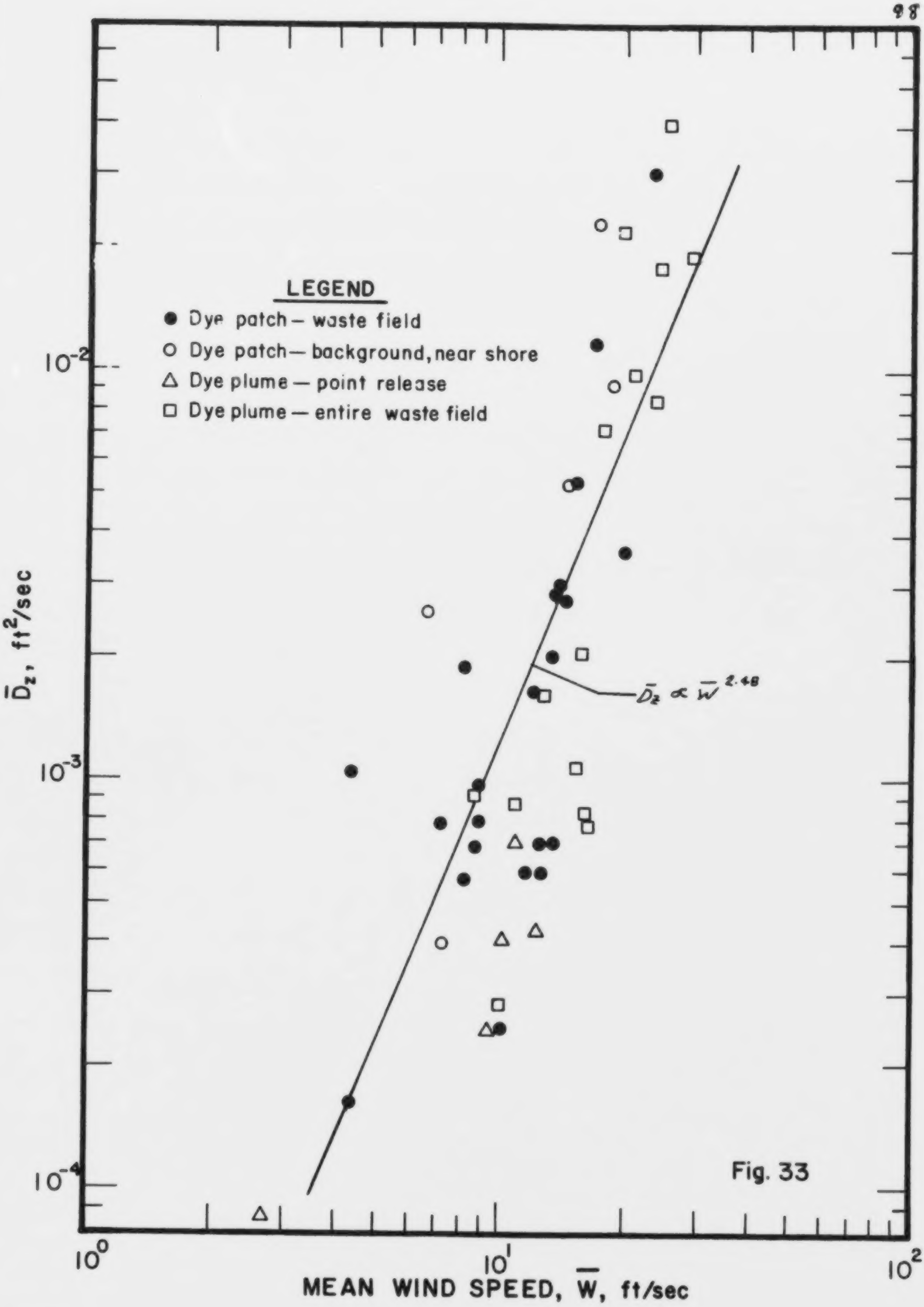

LEGEND
● Dye patch — waste field
○ Dye patch — background, near shore
△ Dye plume — point release
□ Dye plume — entire waste field
$\bar{D}_z \propto \bar{W}^{2.48}$
10^{-2}
10^{-3}
10^{-4}
$\bar{D}_z$, ft^2/sec
10^0
10^1
10^2
MEAN WIND SPEED, $\bar{W}$, ft/sec

Fig. 33

Significance of Source Size in Oceanic Dispersion

Introduction

An inspection of the proposed dispersion equations shows that the initial size of continuous waste plumes strongly influences the rate of physical dilution. For simplicity we will consider equation(29) in assessing this influence. In this equation the effects of lateral and vertical diffusion are included in the product

$$\left[\frac{2\,D_y X}{U\,\sigma_{yo}^{2}}+1\right]^{1/2}\left[\frac{2\,D_z X}{U\,\sigma_{zo}^{2}}+1\right]^{1/2} \qquad (33)$$

It is evident from the data shown in Figure 32 that the larger the initial size, σ_{yo}, the larger the predicted value of D_y. However, since σ^2_{yo} appears in the denominator of the above equation, the significance of a larger lateral coefficient is considerably reduced; this is particularly true near the origin of the plume.

The same reasoning applies to the vertical spread of waste. Although D_z was found in these experiments to be independent of the initial plume size, relatively large values of σ^2_{zo} will tend to control the initial rate of vertical diffusion.

Equation (29) also shows that the rate of minimum dilution varies with distance along the central axis of the plume. In general small-scale plumes will have higher initial rates and lower or nearly equal subsequent rates of dilution than comparably larger-scale plumes. This does not mean that plumes of smaller initial size will yield superior total dilution characteristics. In this case it is necessary to consider the total dilution of the plume. As mentioned previously, total dilution is considered to be due to the combined effects of initial dilution close to the outlet and subsequent dilution of the resulting plume.

An example problem illustrating these effects is presented below. However, it is of interest to first consider methods currently available for predicting the initial size of a waste plume for a given set of oceanic conditions.

Density Spread of a Waste Field

When a waste flow of relatively fresh waster is discharged into the ocean, density differences cause the plume to rise to some equilibrium level over the outlet. On reaching this level sufficient buoyancy may remain to produce an initial spread of waste material. This effect was noted by the Allan Hancock Foundation (1965) in diffusion experiments conducted on the Orange County Outfall. In this case a relatively large waste flow (see Table 3) was discharged through a simple open-ended pipeline. The waste plume rose to the surface forming a turbulent "boil" from which the waste spread in all directions. The observed tendency for the waste to spread upstream against the prevailing current as well as in the cross-current direction was attributed to the hydraulic head produced by residual momentum of the rising plume. It is now recognized that the initial spread of material could also have been brough about by resulting density differences between the waste plume and background water.

Harremoes (1967) presented an extensive review of this subject and discussed various theoretical concepts which show that buoyancy can influence and possibly control the lateral spread of a waste plume, especially near the origin. The intent here is not to review this subject in great detail but to present the theoretical models proposed by Harremoes from which estimates of the initial size of a plume can be made.

According to Harremoes the initial width and depth of a continous plume due to buoyancy is dependent upon the prevailing current velocity as compared to the so-called critical velocity for a given outfall. The critical velocity, U_c, is defined as that velocity due to buoyancy which just equals the prevailing current velocity, U, and is defined by the equation

$$U_c = \left[\frac{\Delta_0 g q}{2R}\right]^{1/3} \tag{34}$$

Here, q is the discharge per outlet, R is the radius of the buoyant Jet at the water surface, and $\Delta = \frac{\rho_1 - \rho_2}{\rho_2}$ = the relative difference in density between undiluted waste and receiving water. Thus for waste water discharged into denser ocean water U_c is a function of $^q/R$. The magnitude of this ratio depends on the type of outfall; for outfalls with multi-port diffusers q is relatively small, and Harremoes estimates U_c to be in the order of 0.3 ft/sec. For single outlet outfalls the discharge (q = Q) is relatively larger as is U_c. In the present experiments the maximum value of U_c for an outfall with a single outlet (Orange County) was estimated to be about 1.7 ft/sec.

A comparison of these estimates of critical velocities with the data shown in Table 3 shows that in most of these experiments the observed velocity was less than the estimated range of critical velocities. This situation is defined by Harremoes as subcritical conditions. For this case the initial width and depth of a surface plume emanating from a single outlet may be estimated from the following equations:

$$W_0 = \frac{\Delta_o g Q}{U^3} \tag{35}$$

and

$$H_0 = \frac{U^2 S}{\Delta_o g} \tag{36}$$

where Q is the total rate of discharge and S is the mean initial dilution of waste between the point of release and the water surface. It is important to note that in the derivation of these equations it was assumed that the plume cross-section is rectangular in shape and the density of the waste-sea water mixture constant throughout.

For the case of multi-port diffusers with a certain current velocity less than U_c, the individual plumes from each outlet will merge at the line of the outlets forming one large surface plume. Designating the current velocity for this condition as U_m, Harremoes presented the following equations for the initial width and depth of the plume:

$$W_0 = Na \; ; \quad U = U_m \tag{37}$$

and

$$H_0 = \frac{SQ}{NaU} \quad ; \quad U \overline{<} U_m \tag{38}$$

where n is the number of ports and a is the port spacing.

When the velocity of flow becomes less than U_m the width W_0 will be larger than Na and the depth different from that given by equation (38). Harremoes stated that when W_0 increases to about an order of magnitude greater than Na the outfall behaves as a large single outlet. For this condition the initial width and depth may be estimated from equations (35) and (36). The problem here is that within the transition zone ($U < U_m$) from $W_0 = Na$ to about 10 Na. There is no formula presently available to compute the increase in W_0 with decreasing current velocity. In this case empirical relationships will have to suffice, at least for the time being, for estimates of initial width.

The above equations can be modified to fit the results of the present experiments by substitution of the approximate relationships for plume width and depth obtained from the characteristics of Gaussian concentration distributions. Thus $W_0 \doteq 4\,\sigma_{yo}$ and $H_0 \doteq 2\,\sigma_{zo}$. Since the plume cross-section was observed to be semi-elliptical in shape, the initial cross-sectional area was calculated as $A_0 = 4\,\pi\,\sigma_{zo}\,\sigma_{yo}$.

In order to investigate the applicability of the above formulas we will consider first the case of the observed initial lateral spread of dye concentration. The ratio of the approximate observed initial width, $4\,\sigma_{yo}$, to diffuser length, $Y = Na$, for all outfalls is presented in Figure 34. Although the data points

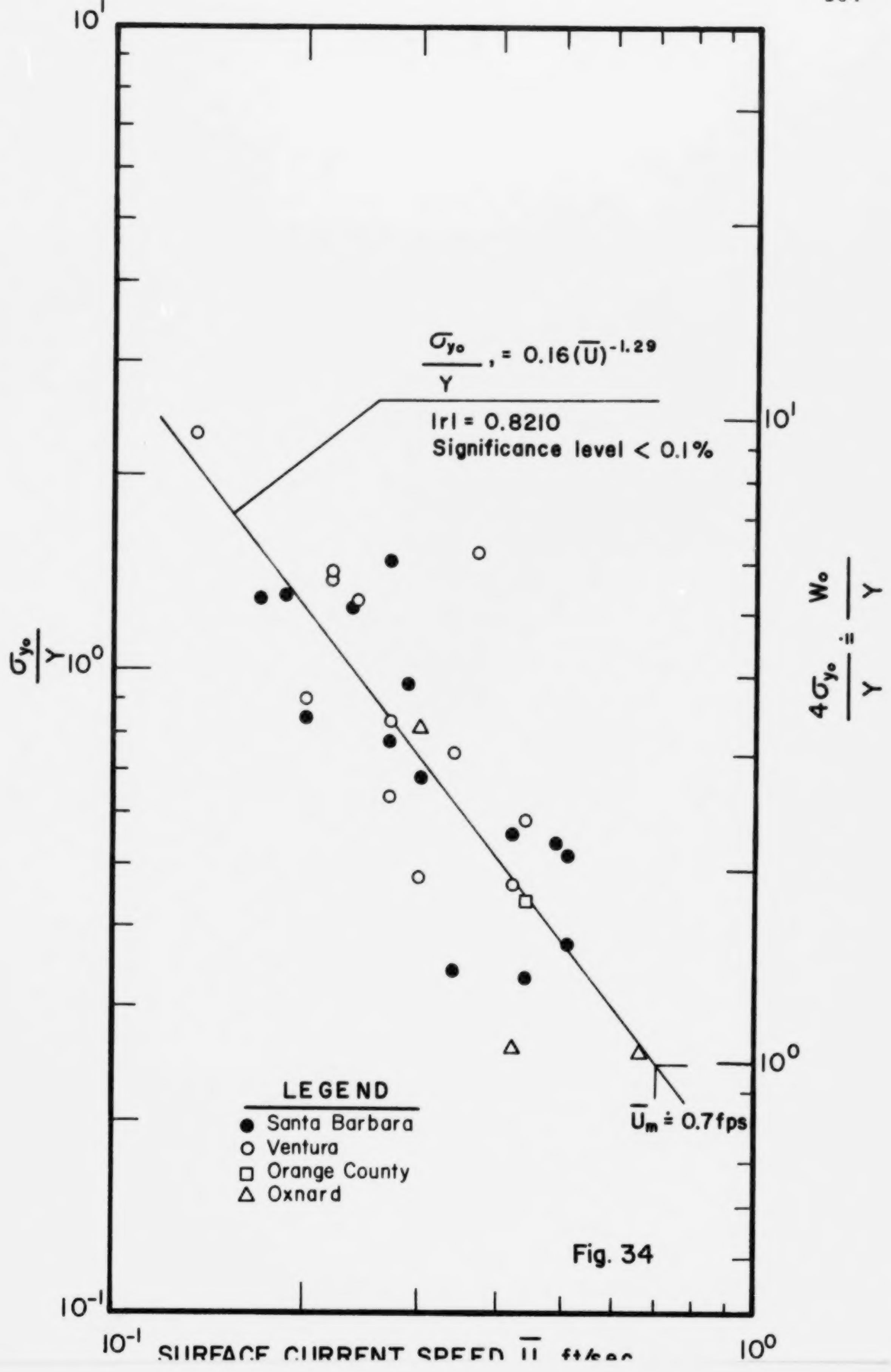

10^1
$\frac{\sigma_{y_0}}{Y}, = 0.16(\overline{U})^{-1.29}$
$|r| = 0.8210$
Significance level < 0.1%
σ_{y_0}/Y
10^0
10^{-1}
10^1
10^0
$\frac{4\sigma_{y_0}}{Y} \doteq \frac{W_0}{Y}$
$\overline{U}_m \doteq 0.7$fps
LEGEND
● Santa Barbara
○ Ventura
□ Orange County
△ Oxnard
10^{-1}
SURFACE CURRENT SPEED $\overline{U}$ ft/sec
10^0

Fig. 34

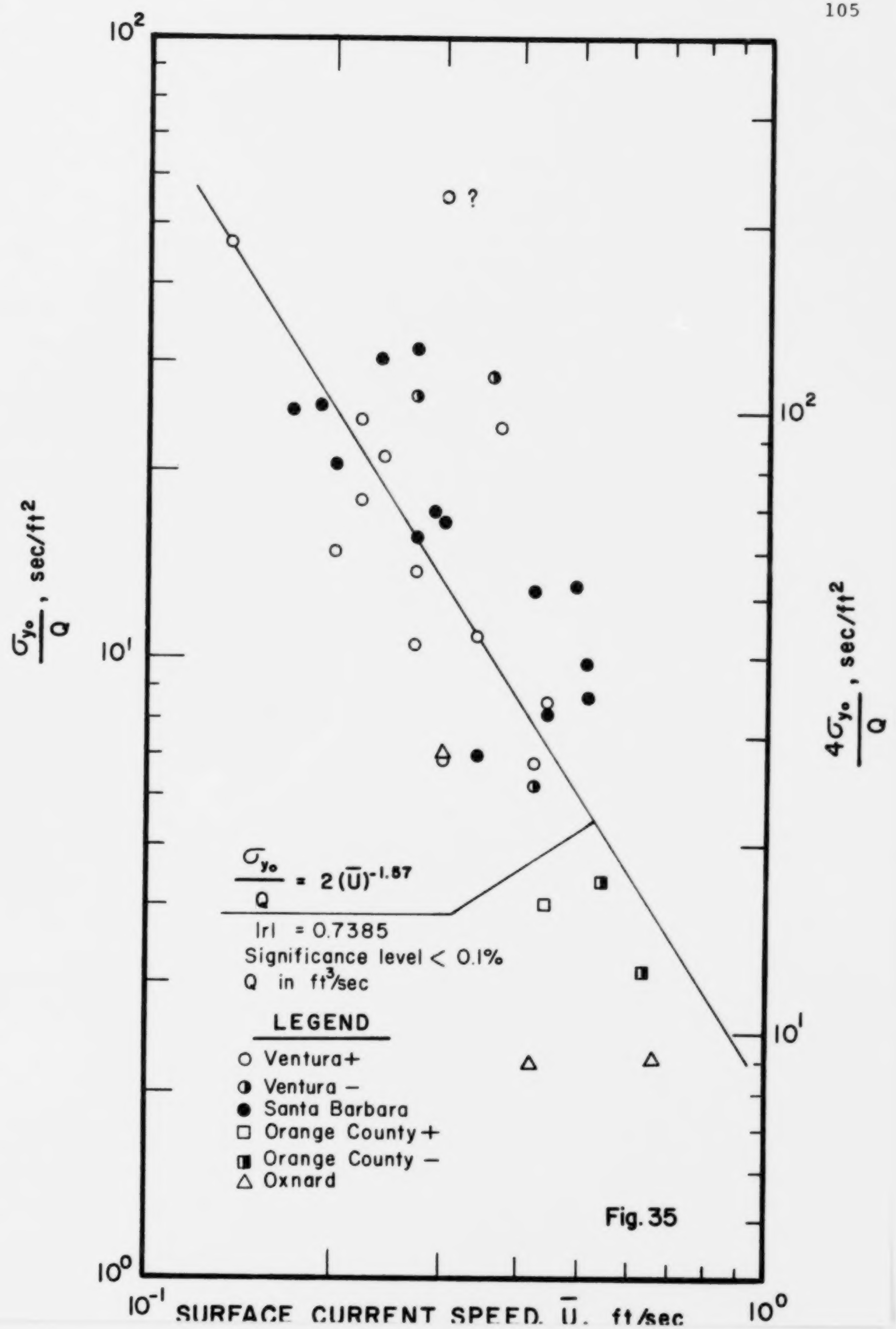

10^2
10^1
10^0
$\frac{\sigma_{y_o}}{Q}$, sec/ft^2
$\frac{4\sigma_{y_o}}{Q}$, sec/ft^2
10^2
10^1
10^{-1}
SURFACE CURRENT SPEED, $\overline{U}$, ft/sec
10^0
?
$\frac{\sigma_{y_o}}{Q} = 2(\overline{U})^{-1.87}$
$|r| = 0.7385$
Significance level $< 0.1\%$
Q in ft^3/sec
LEGEND
○ Ventura+
◐ Ventura −
● Santa Barbara
□ Orange County +
◨ Orange County −
△ Oxnard

Fig. 35

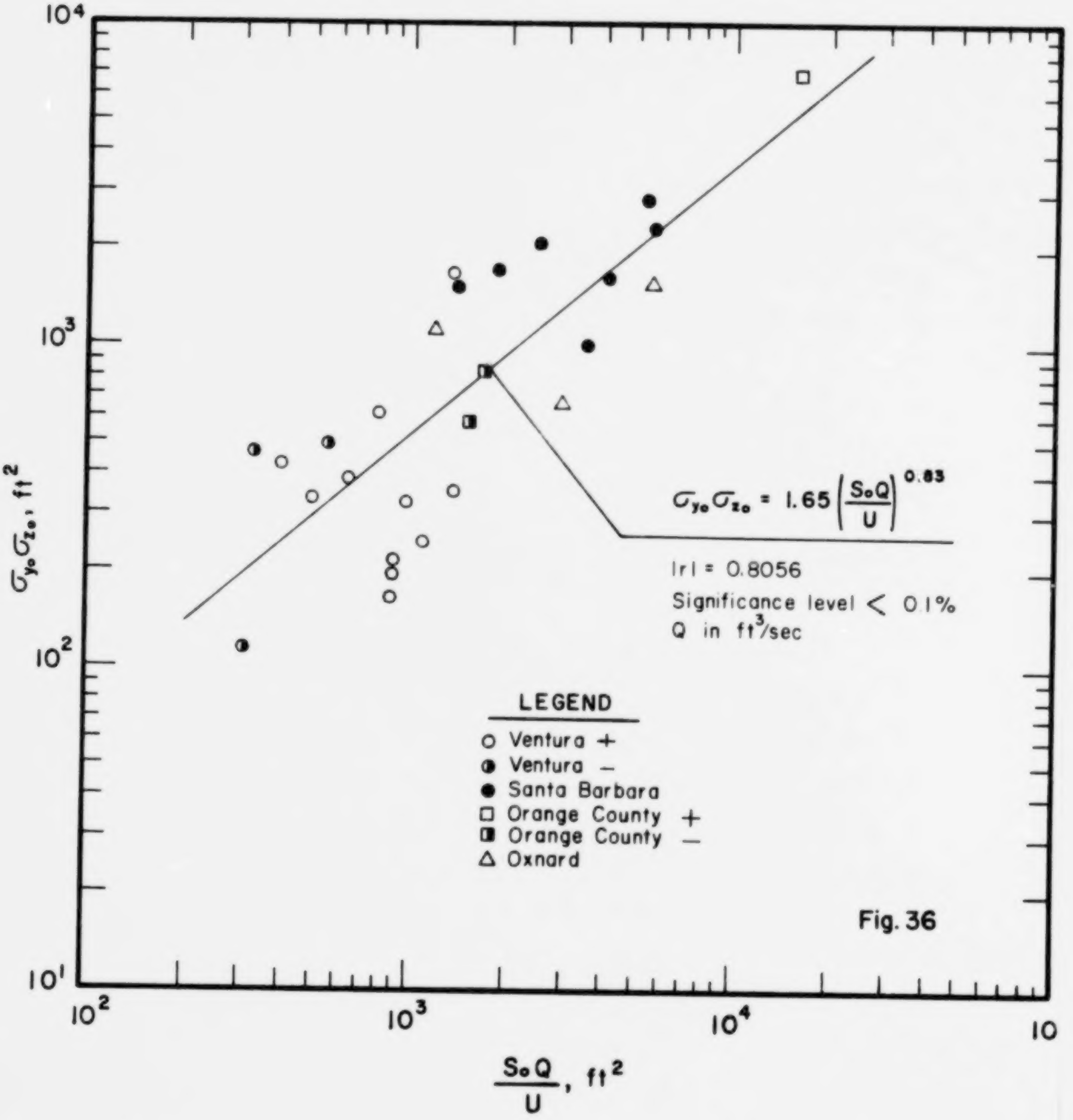

10^4
10^3
10^2
10^1
$\sigma_{y_0}\sigma_{z_0}$, ft^2
10^2
10^3
10^4
10
$\frac{S_0 Q}{U}$, ft^2
$\sigma_{y_0}\sigma_{z_0} = 1.65 \left(\frac{S_0 Q}{U}\right)^{0.83}$
$|r| = 0.8056$
Significance level $< 0.1\%$
Q in ft^3/sec
LEGEND
○ Ventura +
◐ Ventura –
● Santa Barbara
□ Orange County +
◧ Orange County –
△ Oxnard

Fig. 36

scatter somewhat, there is a strong trend for $^{W}0/y$ to decrease with increasing current velocity. It is evident that in all experiments the initial width was greater than the diffuser length; thus indicating that $U < U_m$. It is also evident that in only one experiment was the value of $4\,\sigma_{yo}$ near one order of magnitude greater than $\underline{Y}$. Consequently, on the basis of the above the performance of these outfalls was considered to be in the so-called transition zone. For this condition the lateral spread cannot be predicted from purely theoretical considerations. If, however, the performance of these outfalls was assumed to be that of a large single outlet ($U << U_m$), the lateral spread should follow equation (35). Consequently we would expect to find

$$\frac{4\,\sigma_{yo}}{Q} \propto U^{-3} \qquad (39)$$

That this was not the case is demonstrated by the data shown in Figure 35. Although there is a highly significant correlation between the variables, the slope of the trend line is -1.57 and not -3.0 as predicted from theory.

From a practical point of view the data shown in either Figures 34 or 35 provide an empirical means of estimating the initial lateral size of a surface plume. Additional research is required to assess the applicability of these empirical results to other near-shore coastal areas.

The data presented in Figure 34 show that for these experiments $U_m \doteq 0.7$ ft/sec. and that the observed current speeds were less than this value. For this condition the continuity equation can be used to estimate H_0. Thus for an assumed Gaussian concentration distribution of semi-elliptical plume cross-section we have from equation (38)

$$H_0 \doteq 2\,\sigma_{yo} \doteq \frac{SQ}{2\,\pi\,\sigma_{yo}U} \tag{40}$$

In these experiments only the mean minimum initial dilutions, $S_0 = \frac{C_p}{C_0}$, were computed. Assuming the mean dilution, S, is proportional to S_0 we can express equation (40) as

$$\sigma_{zo} \doteq \frac{k\ S_0\ Q}{\sigma_{yo}\ U} \tag{41}$$

or

$$\sigma_{yo}\,\sigma_{zo} \doteq \frac{k\ S_0 Q}{U} \tag{42}$$

The applicability of equation (42) to the results of the present experiments is shown by the data presented in Figure 36. Although these data were collected from experiments on relatively large and small outfalls with a wide range of environmental conditions, there is a highly significant correlation between the variables. In addition the slope of the trend line is 0.83 which is close to the theoretical value of 1.0 predicted by equation (42).

These results merely reflect the fact that the continuity equation can be used to estimate the initial depth of a surface plume providing the other variables are known or can be estimated by other means.

Illustration

With the data presented above it is now possible to assess quantitatively the influence of the initial plume size on the decrease in maximum waste concentration. As an example we will consider the relative rates of dilution of two plumes emanating from two multi-port diffusers of significantly different lengths. The initial conditions are assumed to be

$Q = 10$ cfs

$C_p = 1$ ppm

$U = 0.5$ fps U_m

$W = 17$ fps

$Y_1 = 100$ ft

$Y_2 = 1000$ ft

$\sigma_{zo} = 10$ ft

For the smaller diffuser we have from Figure 34, $\sigma_{yo}/y = 0.38$ and $\sigma_{yo} = 38$ ft. With this value of σ_{yo} and Figure 32 we find $D_y \doteq 0.95$ ft/sec. Entering Figure 33 with a mean wind speed of 17 fps yields $D_z \doteq 3.8(10)^{-3}$ ft^2/sec. Normally the next step in this type of analysis would be to estimate the initial dilution of the waste by the methods proposed, for example, by Rawn, Bowerman, and Brooks (1960). With this value of S_0 the continuity equation (42) could be solved for σ_{zo}. The intent of this example problem is not to discuss formulas pertaining to diffusers of a particular design· hence, in this problem an assumed value of σ_{zo} will be used. This assumption should not affect significantly the comparison which follows.

The initial maximum concentration is from equation (15)

$$C_0 = \frac{(10)(1)}{(3.14)(0.5)(38)(10)}$$

$$= 0.016 \text{ ppm}$$

Substitution of the above values into equation (29) for $^C/C_0$ yields the results shown in Figure 37. For purposes of comparison the curve for the distribution of maximum concentration along the plume centerline is also shown.

The same procedure was followed for the case of the larger outfall and the results presented in Figure 37. It is evident from the curves for the $^C/C_0$ vs X that the smaller the initial size of the plume the greater the rate of subsequent dilution. However, the curves for maximum concentration show significantly lower values along the axis of the plume from the larger diffuser. This result is of course due to the much higher initial dilution obtained from a source of relatively larger size.

These results are in accord with those obtained by Hyperion Engineers, Inc. (1957) in the design of a submarine outfall in Santa Monica Bay, California.

From an engineering point of view the choice of the type and size of diffuser to use in a particular situation depends on many factors. For a detailed review of this subject see, for example, Harremoes (1968).

The intent of the above discussion was to demonstrate, through the use of the proposed dispersion equations, the influence of source size on the subsequent rate of dilution at the ocean surface.

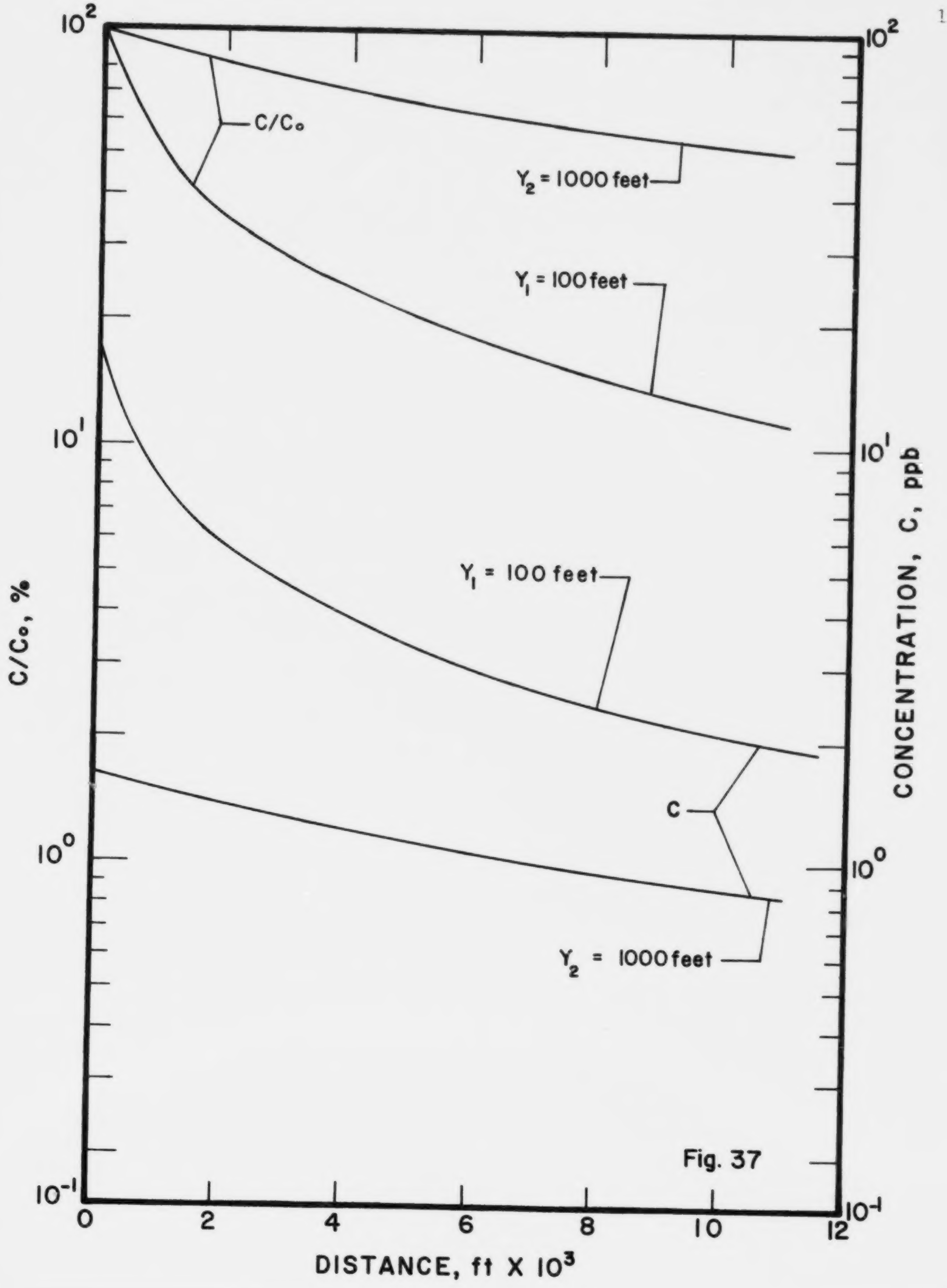

C/Co
Y_2 = 1000 feet
Y_1 = 100 feet
Y_1 = 100 feet
C
Y_2 = 1000 feet
C/Co, %
CONCENTRATION, C, ppb
DISTANCE, ft X 10^3
10^2
10^1
10^0
10^{-1}
0
2
4
6
8
10
12

Fig. 37

In this regard it is of interest to note that the proposed models can also be used to estimate maximum mean concentration distributions for submerged waste plumes by substituting Q/2 for the discharge and 4 σ_{zo} for the initial plume depth where appropriate. The problem here, however, is that little is known concerning the effect of density stratification on the magnitude of the diffusion coefficients. It is possible that strong density stratification may result in significantly lower apparent diffusion coefficients than observed at the water surface. More research is needed on this subject.

Factors Affecting Bacterial Die-Away

Introduction

The environmental factors which may effect the disappearance of enteric bacteria in the ocean were discussed in detail in a previous section of this report. The intent of this section is to assess both qualitatively and quantitatively the effects of some of these factors on observed population trends of Coliform and Fecal streptococcus organisms.

Experimental Results - Coliform Bacteria

Some of the experimental findings pertaining to the derivation of equations for bacterial disappearance were presented previously. It was mentioned at that time that both indicator groups exhibited tendencies toward an initial increase or decrease in population near the origin of the surface waste plumes. One method of investigating this phenomenon is by comparing the calculated initial slopes of the best-fit population curves with observed environmental conditions.

Initial Rate of Change. The initial rate of change of relative bacterial concentration can be expressed by taking the derivitive with repsect to time of equation (6).

$$^{C}/C_0 = Y = ae^{-K_1t} + (100-a)e^{-K_2t}$$

thus

$$^{dY}/dt = -K_1 \, ae^{-K_1t} - K_2(100-a)e^{-K_2t} \qquad (43)$$

At the origin of the plume this equation reduces to

$$(^{dy}/dt)_0 = -[K_1 a + K_2(100-a)] \qquad (44)$$

Calculated values of the initial slopes for all experiments are summarized in Tables 5 and 6. Inspection of these results show that in each experiment one of three distinct trends occurred as characterized by the sign of the initial slope. A positive slope indicates initial growth, a negative slope initial die-away, and an essentially zero slope a "neutral" initial condition. A schematic diagram of these population trends together with an arbitrary classification are shown in Figure 38.

From previous discussions in this report it is clear that many environmental factors may have influenced the initial rate of change in bacterial population. On the basis of the results of these experiments the following factors were assumed to have direct influence on the initial rate of change:

a. Sedimentation of indicator bacteria on waste suspended solids.
b. Biological processes such as anti-bacterial action of marine predators, and toxic substances released by marine phytoplankton.
c. Initial rate of subsequent dilution.
d. Mean temperature near the water surface.
e. Initial concentration of indicator bacteria at the origin of waste plumes.

Sedimentation. The influence of this factor was discussed briefly in a previous section of this report. Illustrations of

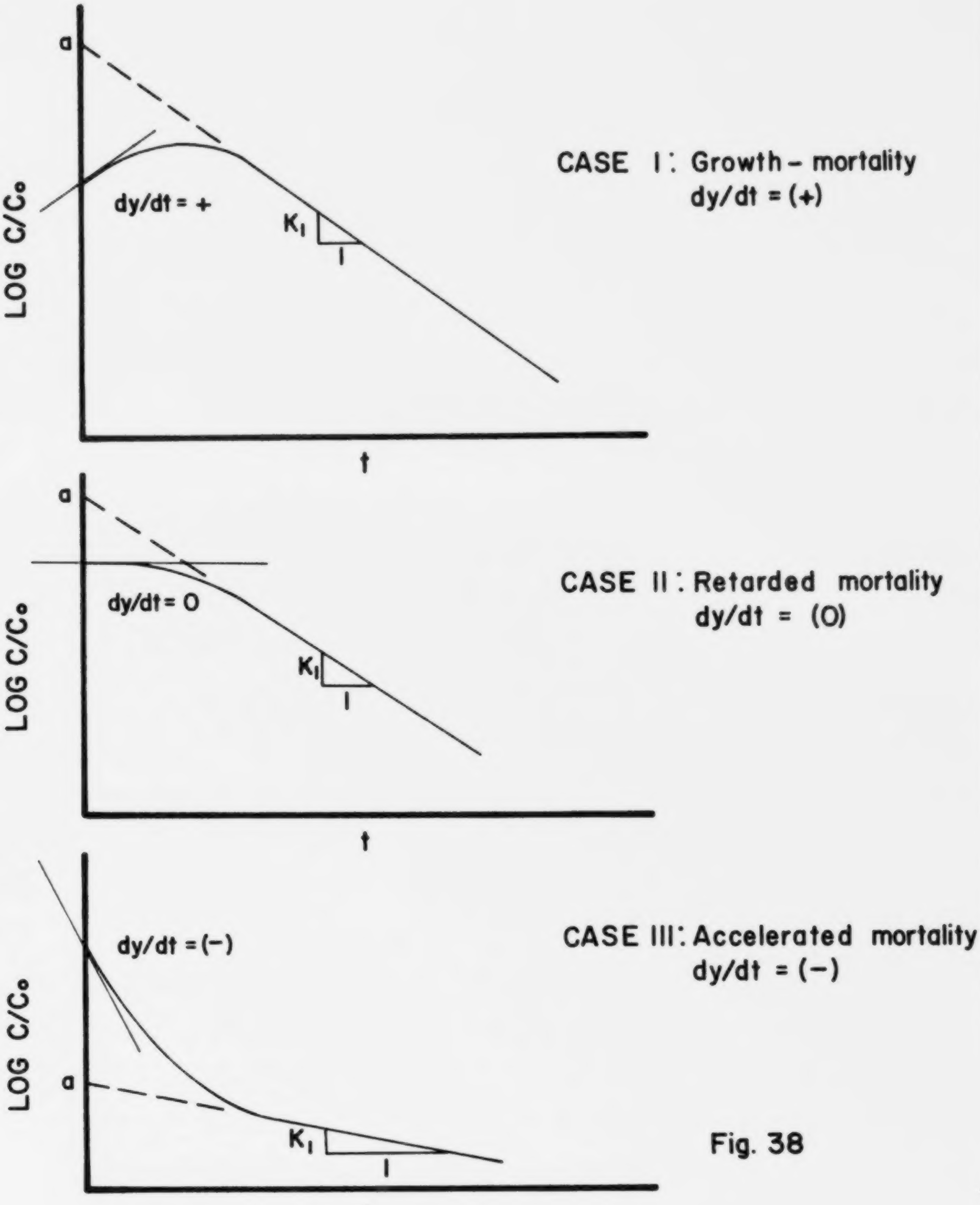
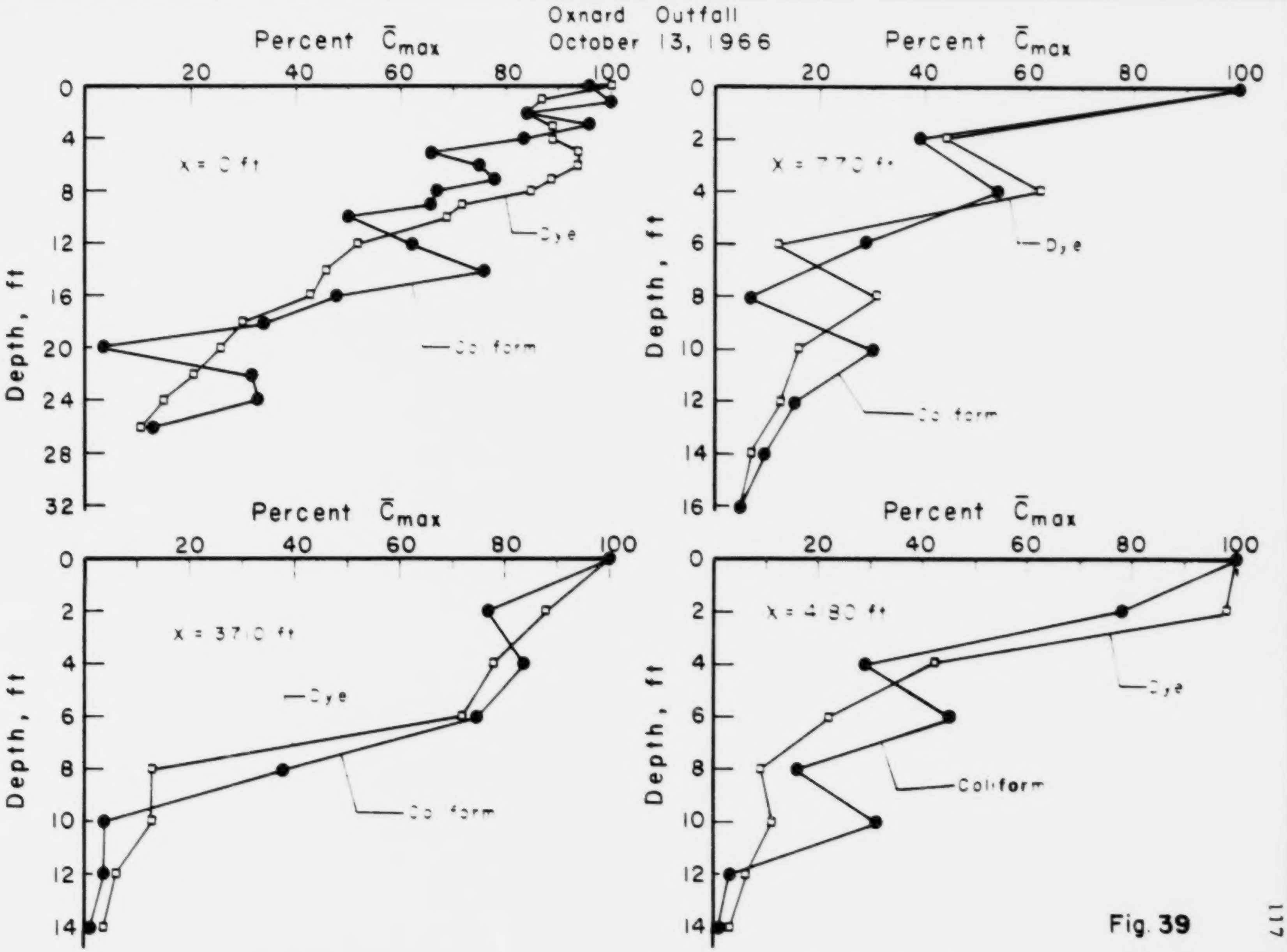

a
LOG C/Co
dy/dt = +
K1
1
t
CASE I: Growth - mortality
dy/dt = (+)
a
LOG C/Co
dy/dt = 0
K1
1
t
CASE II: Retarded mortality
dy/dt = (0)
LOG C/Co
dy/dt = (−)
a
K1
1
t
CASE III: Accelerated mortality
dy/dt = (−)

Fig. 38

the vertical distribution of dye and coliform concentrations were shown therein as a function of distance along a waste plume. It may be recalled that the data presented previously in Figure 22 showed a possible settling out of coliforms along the central axis of a particular waste plume. A tendency for the maximum coliform concentration to be located below the water surface at a depth which increased with distance along the plume was noted in a few experiments. However, in the majority of the experiments the maximum coliform concentration was observed to be at or within a few feet of the water surface all along the plume. A more typical series of vertical coliform distributions is depicted in Figure 39. In this case not only did the mean maximum coliform count remain at the water surface, but the distributions of dye and coliform agreed remarkably well at all depths along the plume. The vertical penetration of both tracers extended to about one half the depth of the water column and remained essentially constant along the plume. The apparent deeper penetration of dye and bacteria at the origin was attributed to the possibility that these samples were taken from the rising column of effluent.

It appears from the results of these experiments that sedimentation of coliforms was not a serious factor. These results may have been due to the type and concentration of solids in the effluents discharged from the outfalls studied. Hyperion Engineers, Inc. (1957) reported that sedimentation of coliforms in the ocean is a function of the type and concentration of suspended solids characteristic of a given waste water. This conclusion was based on the observation that relatively high coliform counts were



Oxnard Outfall
October 13, 1966

Fig. 39

found in the bottom sediments near the terminus of three major outfalls located off southern California. The coliform concentrations were highest for those outfalls discharging unchlorinated primary waste effluent, suspended solids concentration, and the observed rates of coliform disappearance. The results of these analyses were inconclusive. It is possible, as will be discussed subsequently, that the differences in the observed rates of coliform disappearance reported by these authors were due mainly to factors other than sedimentation.

Biological Processes. It is difficult to assess the effects of biological processes on the growth-decay characteristics of enteric bacteria in the ocean. The problem is one of such complexity that only gross effects can hope to be observed from the experimental procedure employed in these studies. One would expect, however, that if the observed growth-decay tendencies of indicator bacteria were strongly influenced by naturally occuring biological agents, there may be a seasonal variation in the concentration of these agents. In this case the initial rate of change of indicator concentration for a particular ecological area would be expected to vary with the season of the year. If this is true the initial slope of the bacterial population curve would also be expected to be related to the initial rate at which the waste water is mixed with background water. In other words the initial rate of change of bacterial population would be a function of the concentration flux of anti-bacterial agents near the origin of the plume.

The fact that the initial slope of the coliform concentration curves varied significantly with season is shown by the data presented in Figure 40. These data are for the oceanic areas around the Ventura and Santa Barbara outfalls. Although separated by a distance of about 20 miles, these areas were assumed to have similar oceanographic and ecological characteristics.

Although there is some scatter of the plotted points in Figure 40, there is an obvious tendency for the initial rate of population change to be negative in the spring and summer months, nearly neutral in the late fall, and positive in the winter. These results correspond to the three arbitrary classifications of population change shown previously in Figure 38.

The apparent seasonal variation in initial slopes is even more striking when these data are plotted as monthly averages as shown in Figure 41.

Subsequent Dilution. The above analyses were made without regard to the initial mixing near the origin of surface plumes. If the apparent seasonal variation shown in Figures 40 and 41 is assumed to be due to anti-bacterial agents present in background waters, thus the rate of input of these agents varies with the rate of initial mixing.

The relationship between the initial rates of population change and subsequent dilution is depicted in Figure 42. The initial rates of dilution shown were obtained by taking the derivitive with respect to time of the best fit curves for relative dye concentration, i.e., $^{C}/C_0 \propto t$, and setting t = 0. The resulting values for all experiments are tabulated in Table 7.

It is apparent from these data that for the grouped data there

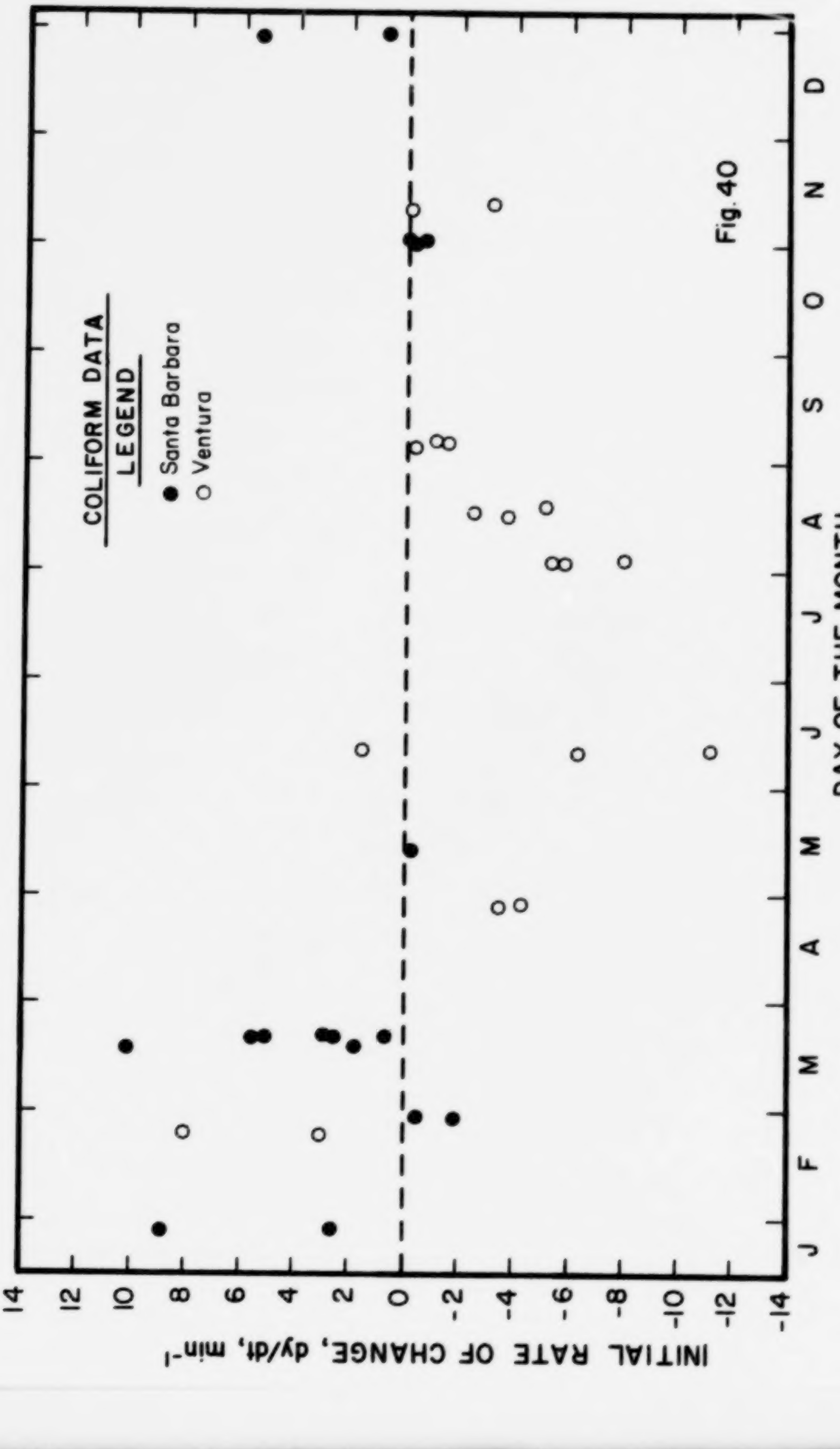

COLIFORM DATA
LEGEND
● Santa Barbara
○ Ventura
INITIAL RATE OF CHANGE, dy/dt, min⁻¹
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
J
F
M
A
M
J
J
A
S
O
N
D
DAY OF THE MONTH

Fig. 40

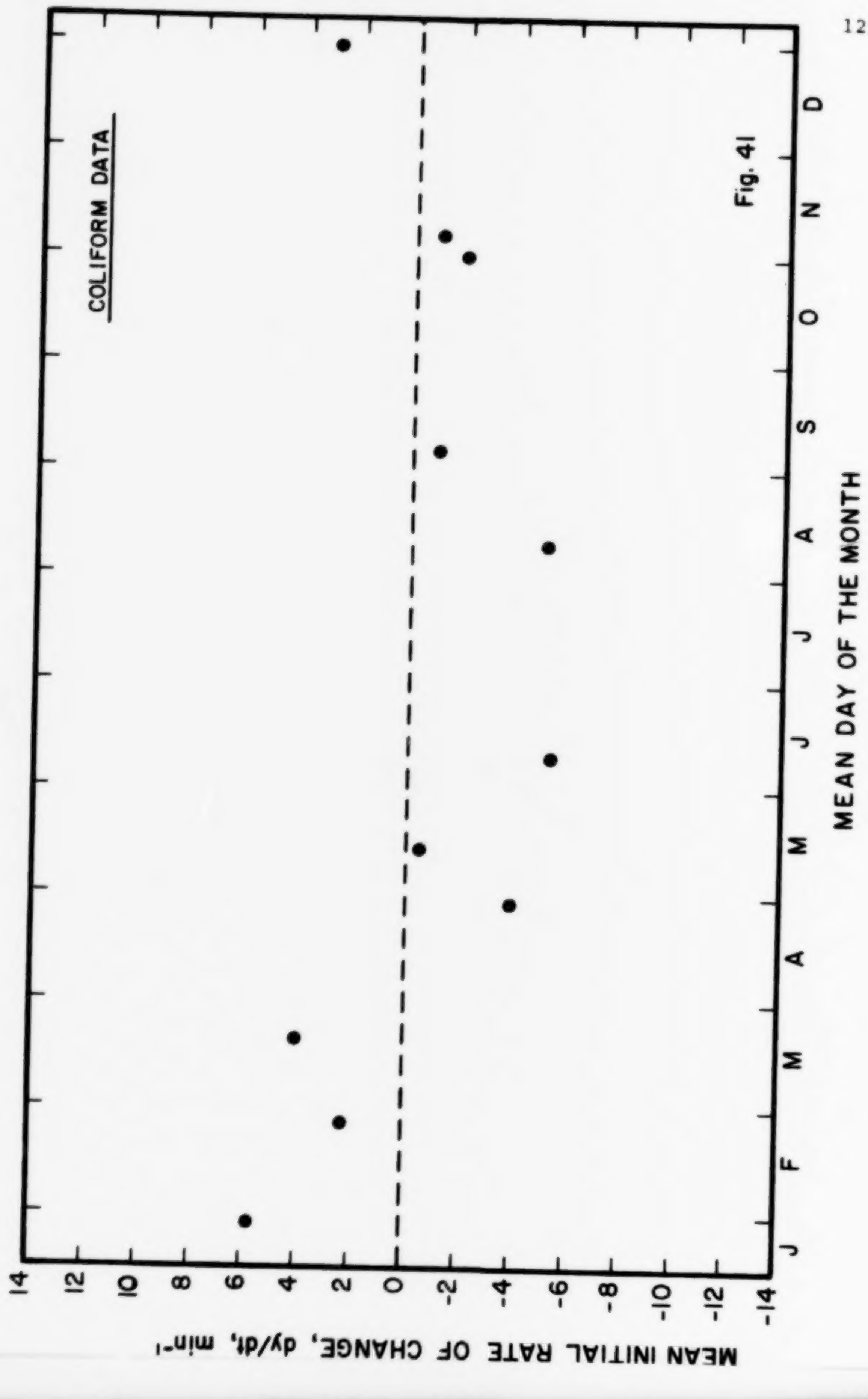

COLIFORM DATA
MEAN INITIAL RATE OF CHANGE, dy/dt, min⁻¹
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

Fig. 41

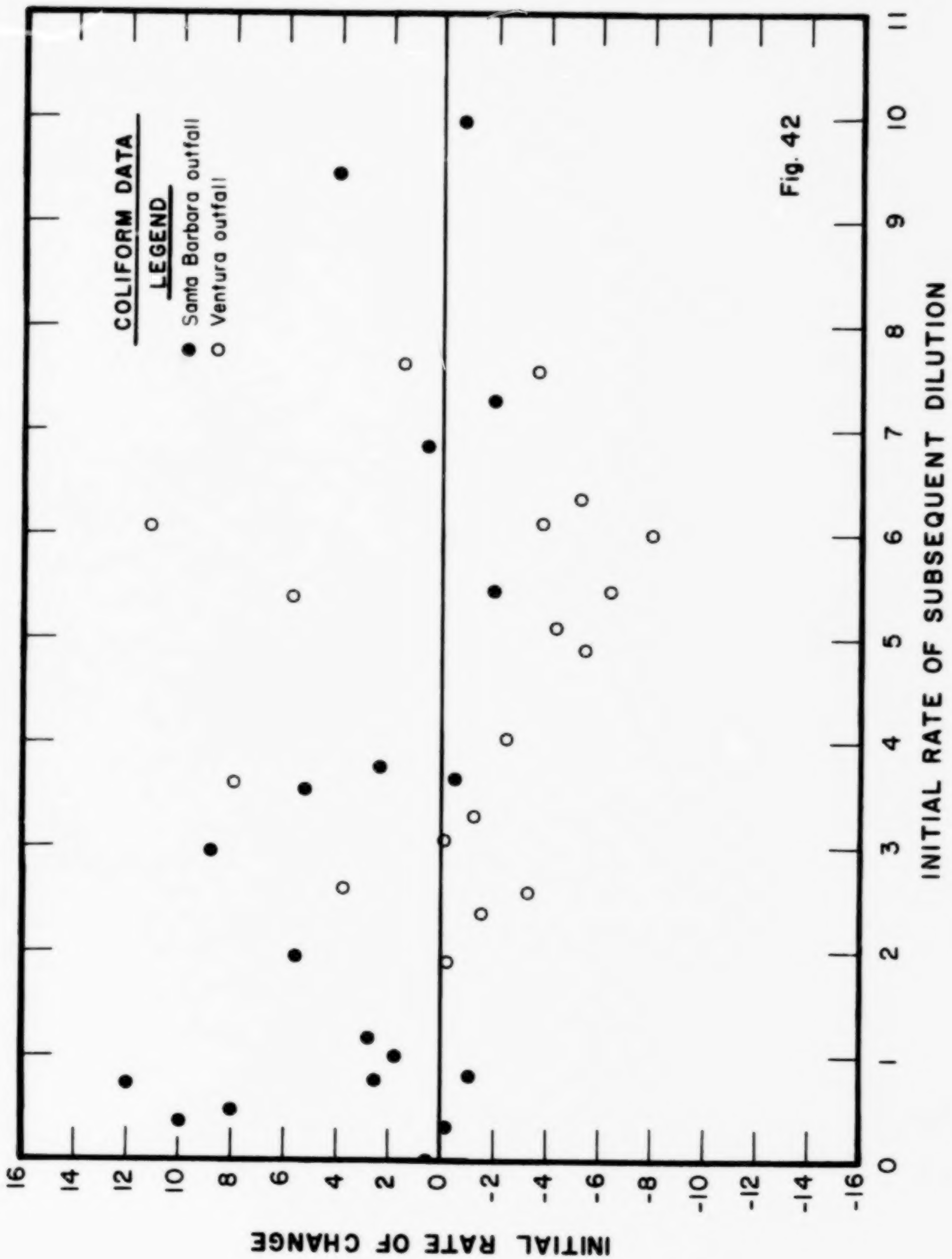

COLIFORM DATA
LEGEND
● Santa Barbara outfall
○ Ventura outfall
INITIAL RATE OF CHANGE
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
INITIAL RATE OF SUBSEQUENT DILUTION
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 42

is a rough trend for positive values of the initial rate of population change to be associated with the lowest rates of initial dilution. As mentioned above a possible explanation of these results is that higher initial rates of mixing, with a constant concentration of anti-bacterial agents, yield a higher input of these agents which suppress any tendency for bacterial growth. On the other hand this hypothesis does not take into consideration any possible seasonal variation in the concentration of anti-bacterial agents or initial rates of mixing. The variation in the calculated initial mixing rates with season is shown in Figure 43. These data indicate that there is a tendency for the mean initial rates to vary seasonally, with the highest values corresponding to the spring and summer months. A comparison of the data presented in Figures 41 and 43 show that, except for the month of December, the trends for both sets of data are quite similar. These results indicate that if the initial slopes of the coliform concentration curves are influenced by anti-bacterial agents, then the concentration of these agents must either remain fairly constant throughout the year or be relatively higher during the fall and winter months. In other words the concentration flux of these agents must be lower during the fall and winter months.

An attempt was made to assess the influence of phytoplankton concentration on the observed initial rates of change of coliform population. The Allan Hancock Foundation (1965) made a series of phytoplankton studies around the Orange County waste outfall off southern California. In these studies both phytoplankton productively and standing crop measurements were made near the water

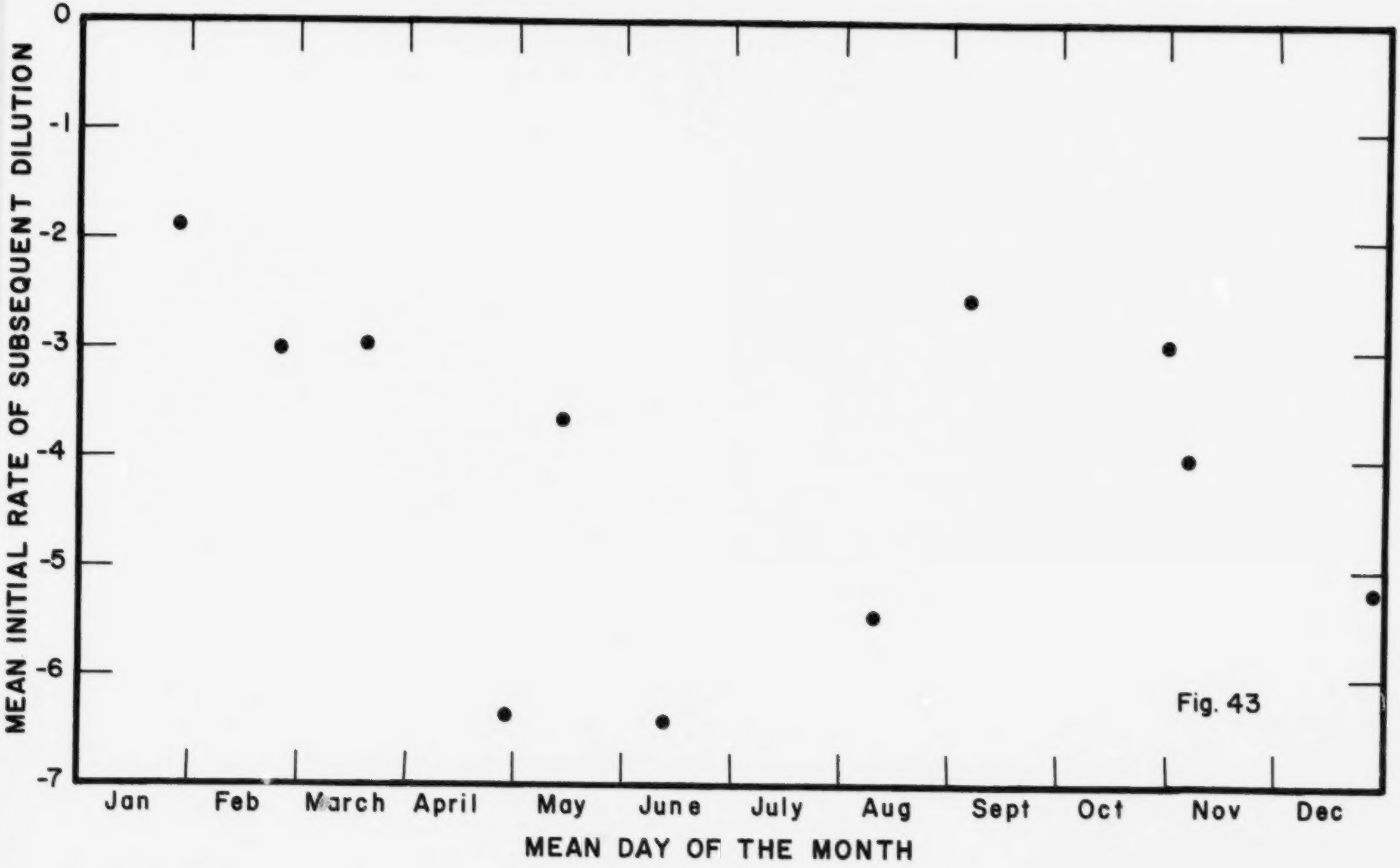

MEAN INITIAL RATE OF SUBSEQUENT DILUTION
0
-1
-2
-3
-4
-5
-6
-7
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec
MEAN DAY OF THE MONTH

Fig. 43

surface of dispersing waste fields at various times of the year. Phytoplankton standing crop measurements were made by analysis for total chlorophyll concentrations as described in the above reference. The results of these experiments are shown in Figure 44 in which the mean values of surface chlorophyll concentration are shown plotted against mean day of the month. It is apparent from these data that the phytoplankton concentration for the areas studied exhibited no definite seasonal trend. Assuming these results are similar to those for the oceanic areas around the Ventura and Santa Barbara Outfalls, it appears that phytoplankton population concentration per se was not responsible for the variation shown in Figure 41. This would indicate that other biological processes, eg, bacterial preditors may have been responsible for the observed phenomenon. Further research is needed on this subject.

Temperature. It has been known for some time that temperature has a strong influence on bacterial growth rates. For coliform and other bacterial indicator organisms the optimum temperature for growth is around 35° C. Temperature higher or lower than this optimum generally produces lower growth rates or increased rates of mortality. Since the surface waters off the coast of southern California are generally lower than this optimum, one would expect the rate of growth to decrease and the rate of mortality to increase with decreasing water temperatures. That this is not the case for the oceanic areas studied is shown by the data presented in Figure 45. These data show that the mean initial rate of change of coliform population actually decreases with

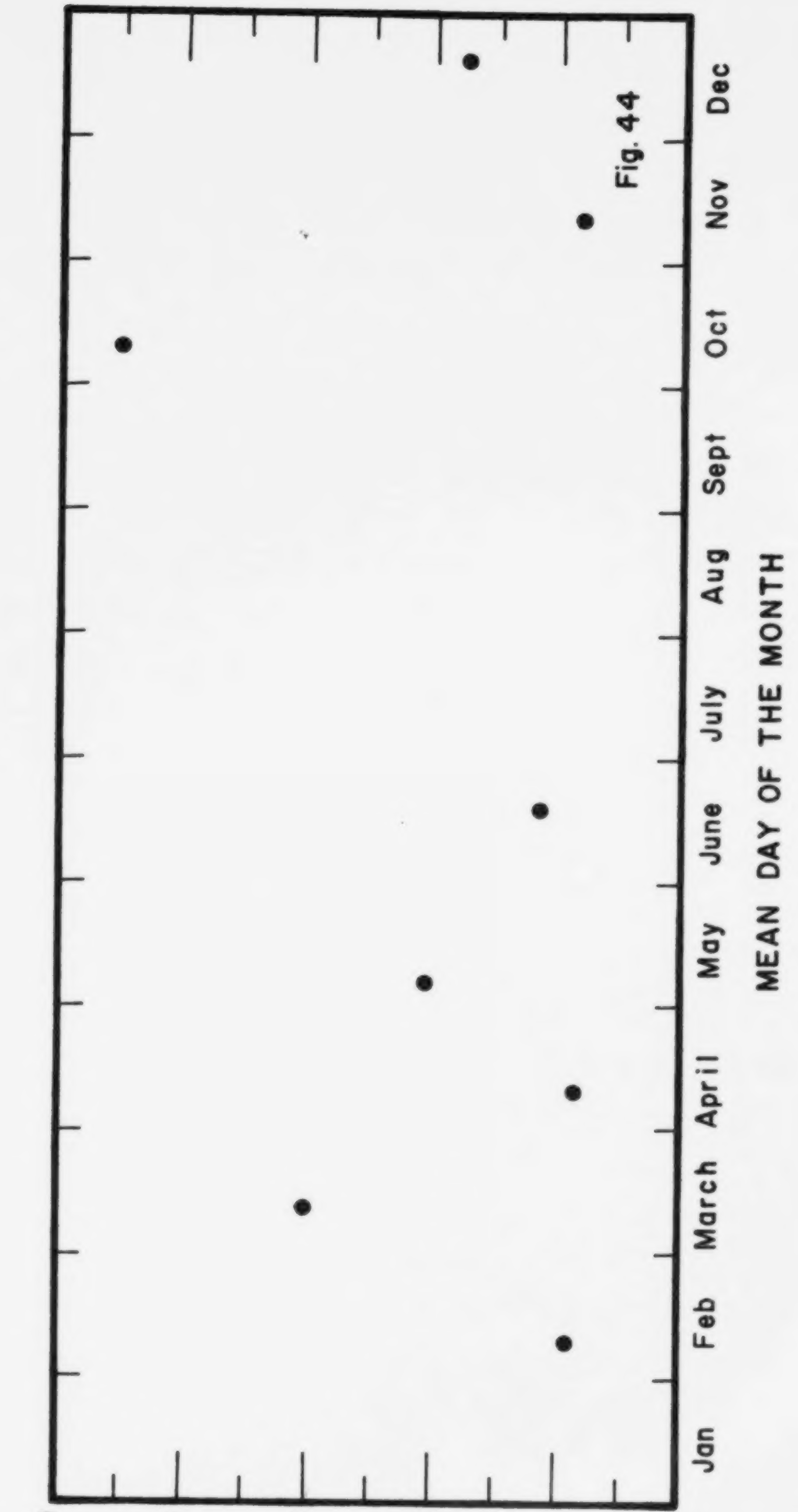

TOTAL CHLOROPHYL, mg/m³
0
10
20
30
40
50
MEAN DAY OF THE MONTH
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec

Fig. 44

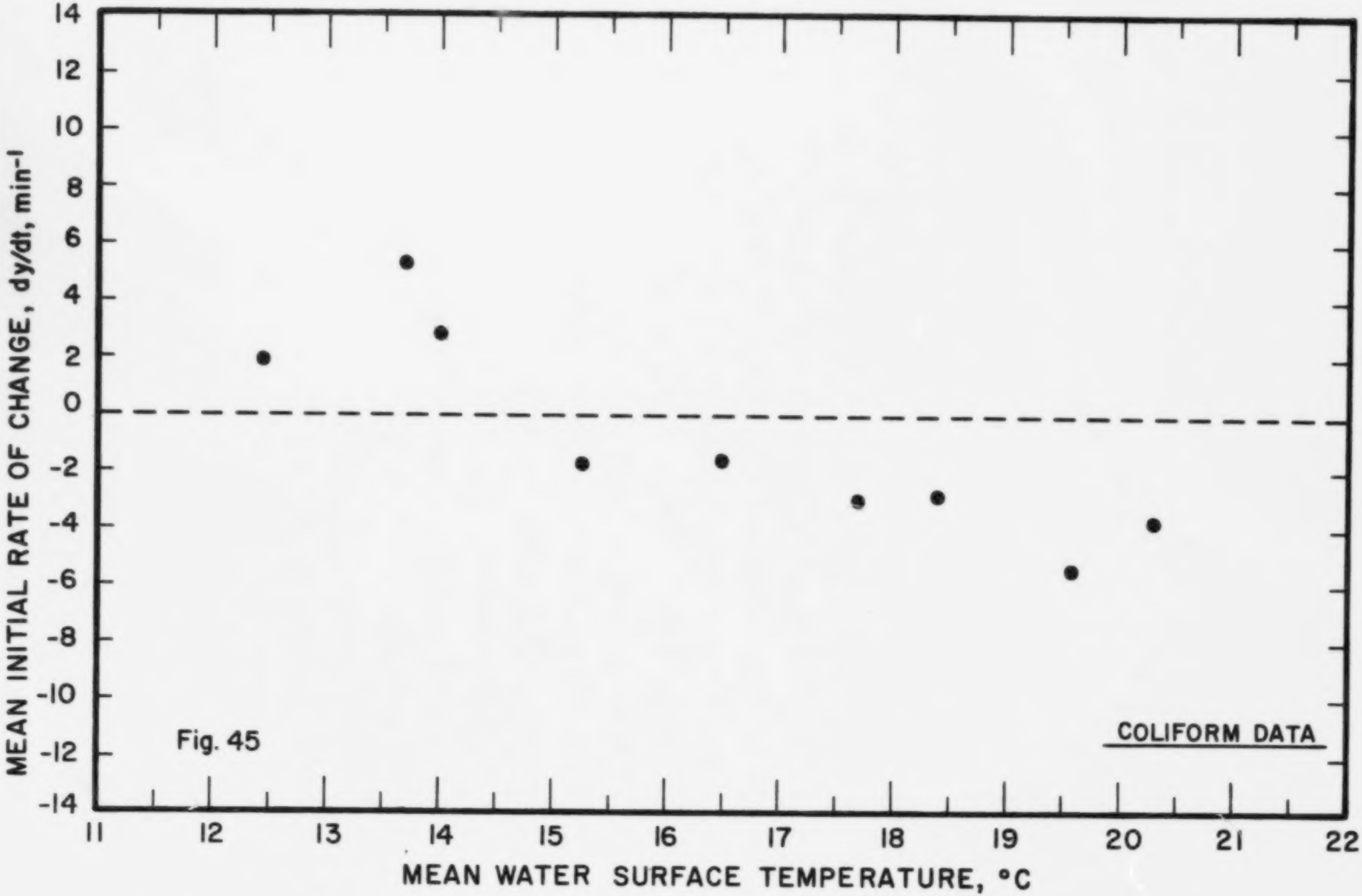


Fig. 45

COLIFORM DATA
MEAN INITIAL RATE OF CHANGE, dy/dt, min-1
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
MEAN WATER SURFACE TEMPERATURE, °C
11
12
13
14
15
16
17
18
19
20
21
22

temperature between about 12° and 20°C. Below a temperature of about 15°C the initial rate is positive and the rate increases with decrease in temperature. Above 15°C the initial rate is negative and becomes more so with increase in temperature.

This apparent anomology was noted by Kittrell and Furfari (1963) among others for coliform disappearance below waste outfalls in fresh water streams. An explanation of this phenomenon, at least for ocean water, can be derived by comparison of the data shown in Figures 41 and 42 with that for mean water surface temperature as presented in Figure 46. It is evident from these data that the mean temperature varied seasonally with minimum values occuring in late fall and winter and maximum values occuring in spring and summer. Thus the data shown in Figure 46 actually reflect the seasonal variations shown in Figures 41 and 42. From this comparison it is possible to hypothesize that increased rates of input of biological agents during the late spring and summer produce a net decrease in coliform concentration which overshadows any increase brought about by higher water temperatures.

Initial Coliform Densities. Assuming the initial rate of change of bacterial population follows a first-order type reaction, it would be expected that coliform concentrations would tend to decrease more rapidly with higher initial concentrations. The relationship between the initial slope of the coliform population curves and the mean initial concentration for all experiments is shown in Figure 47. These data show that there is a tendency for the initial slope to be positive for relatively low initial coliform concentrations and increasingly negative for values of

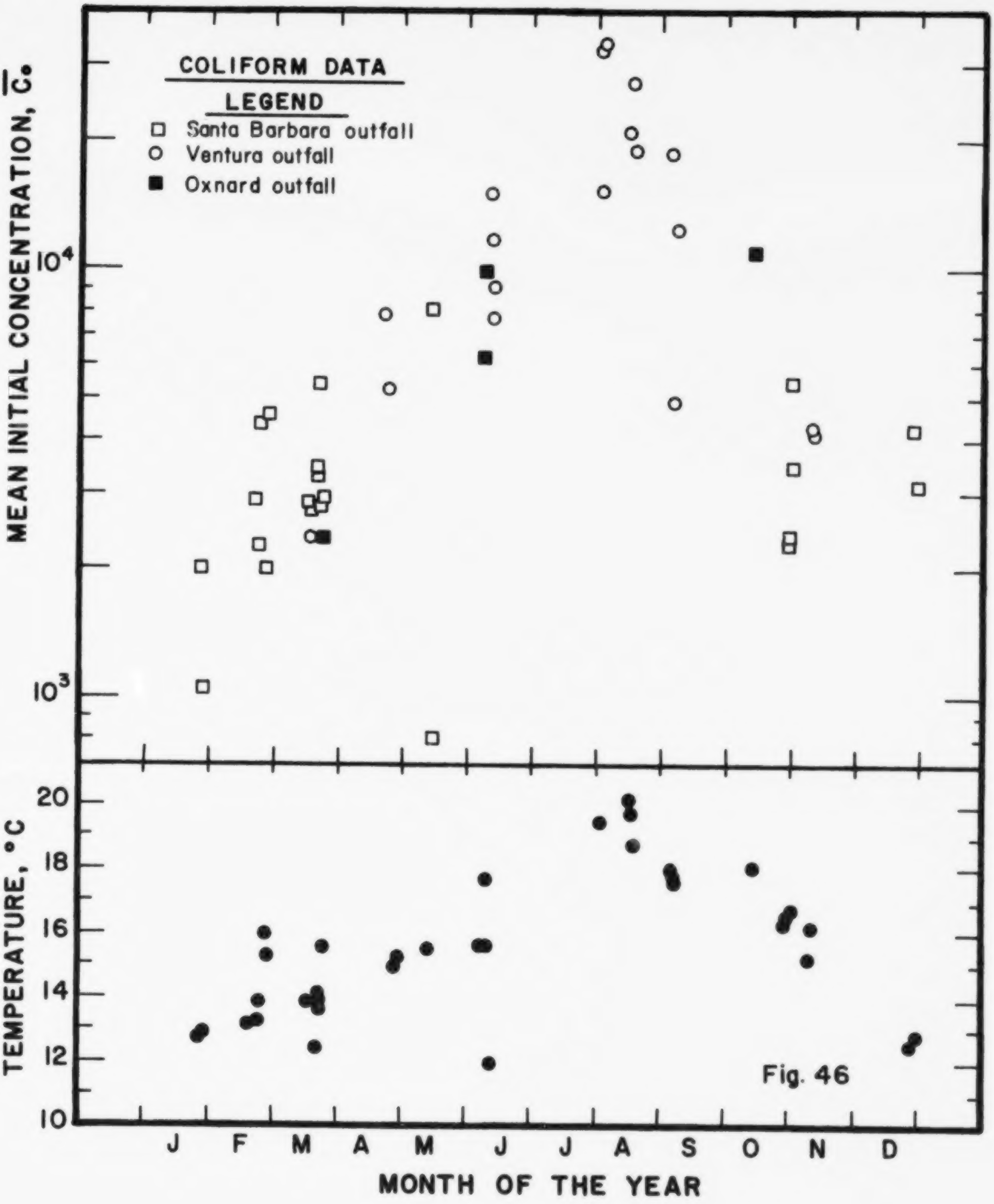

COLIFORM DATA
LEGEND
□ Santa Barbara outfall
○ Ventura outfall
■ Oxnard outfall
MEAN INITIAL CONCENTRATION, $\overline{C}_o$
10^4
10^3
TEMPERATURE, °C
20
18
16
14
12
10
J F M A M J J A S O N D
MONTH OF THE YEAR

Fig. 46

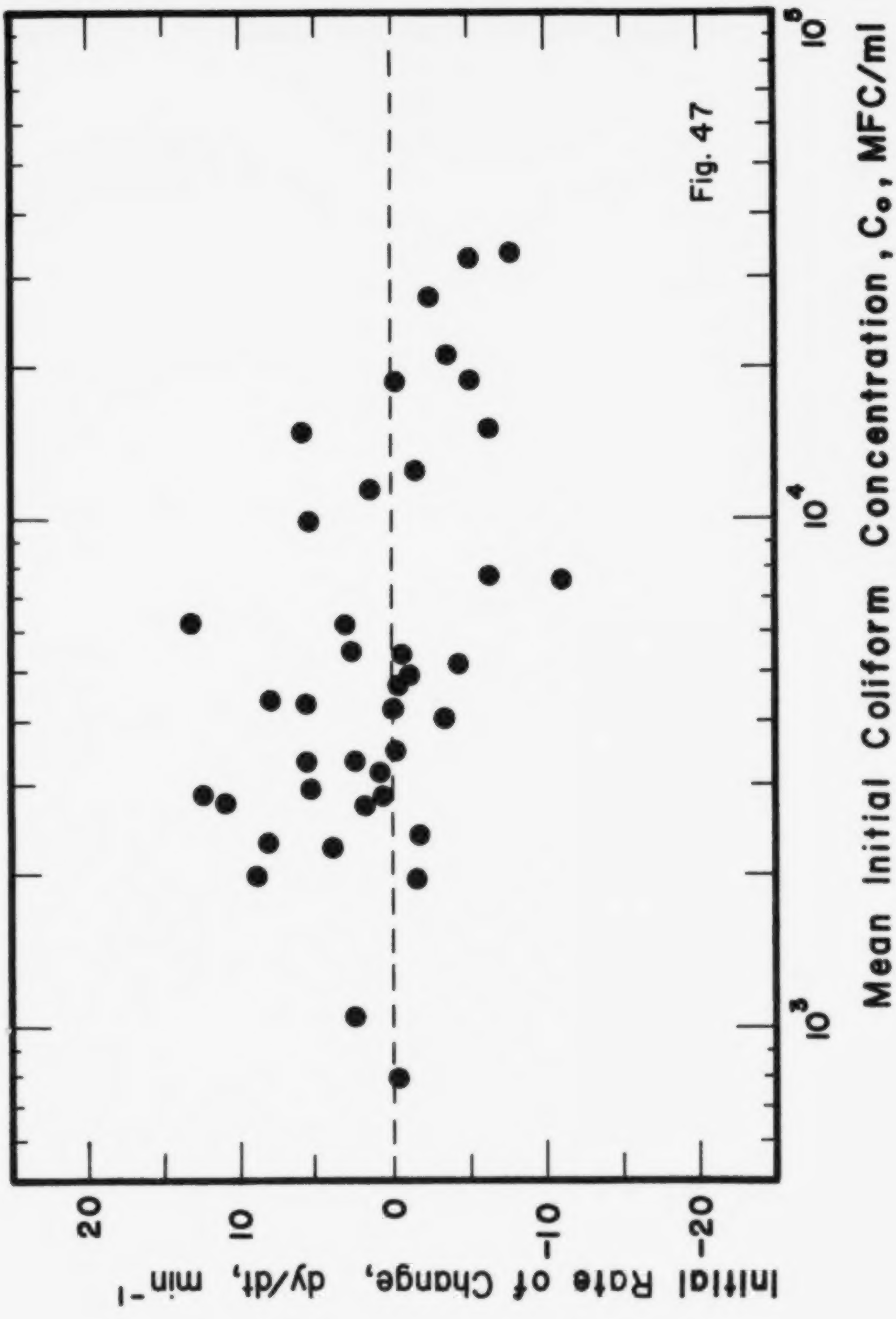

Initial Rate of Change, dy/dt, min⁻¹
20
10
0
−10
−20
Mean Initial Coliform Concentration, C₀, MFC/ml
10³
10⁴
10⁵

Fig. 47

C_0 greater than about 10^4 MFC/ml. Although these data appear to support the above assumption, it can be shown that the initial coliform densities vary seasonally in a manner similar to temperature and other factors as discussed previously. This can be seem from the data presented in Figure 46 which shows that the initial coliform concentration varied throughout the year much the same as mean water surface temperature. From these results it is difficult to assess whether seasonal variations in concentrations of coliform and/or anti-bacterial agents were responsible for the observed variation in initial slopes of the coliform population curves.

It is possible, as pointed out above, that increased concentrations of coliforms or associated nutrients in the waste discharges during the summer months stimulated the production of anti-bacterial agents. Bio-stimulation coupled with higher initial rates of mixing observed to occur during the summer, could have have resulted in relatively high initial rates of coliform mortality.

Whether this hypothesis is valid or not can only be answered by additional research. From a practical point of view, however, data like that shown in Figures 45 and 46 provides the engineer with an empirical means of estimating the initial rate of growth or mortality of coliform bacteria in waste water discharged into the ocean. Further research is needed to assess the applicability of these data to other oceanic environments.

Population Parameters: In the application of equations (3) or (6) to a particular design situation, it is essential that the engineer be able to estimate relevent values of the parameters $\underline{a}$, K_1, and K_2. As in the case of the initial slope of the bacterial population curves, these parameters were found to be related to various environmental factors. In this section an attempt will be made to establish empirical relationships between the population parameters and environmental factors from which reliable engineering estimates can be made. These results, like others presented throughout this report, are limited in application to the particular oceanic areas studied.

As illustrated in Figure 38 the parameter $\underline{a}$ is the intercept of the y-axis at $\underline{t}$ or x=0 of the linear segment of the bacterial concentration curves. The magnitude of $\underline{a}$ is strongly related to the sign of the initial slope-- in general, positive values of $(dy/dt)_0$ are associated with relatively large values of $\underline{a}$ and vice versa. This relationship is shown by the data presented in Figure 48 from which it is evident that positive values of $(dy/dt)_0$ correspond to values of $\underline{a} > 100\%$ and negative slopes to values of $\underline{a} < 100\%$.

Since the initial slopes of the coliform population curves were shown to be related to the season of the year, water temperature, initial rate of dilution, and initial bacterial concentration, similar trends would be expected to obtain between these factors and the intercept $\underline{a}$.

It is apparent from the data presented in Figure 49 that the mean monthly value of $\underline{a}$ varied markedly with the season of

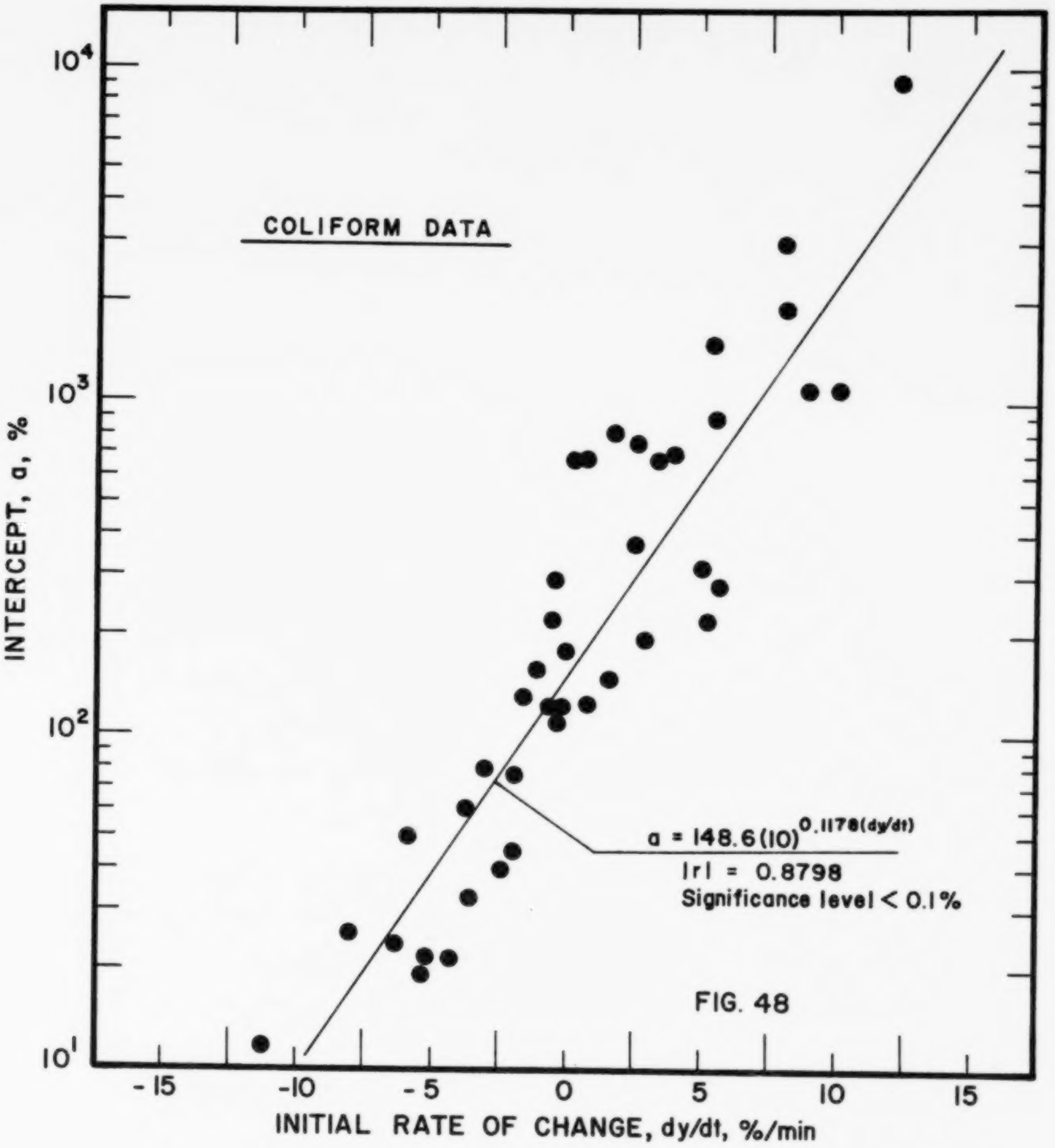

COLIFORM DATA
$a = 148.6(10)^{0.1178(dy/dt)}$
$|r| = 0.8798$
Significance level < 0.1%
INTERCEPT, a, %
10^1
10^2
10^3
10^4
-15
-10
-5
0
5
10
15
INITIAL RATE OF CHANGE, dy/dt, %/min

FIG. 48

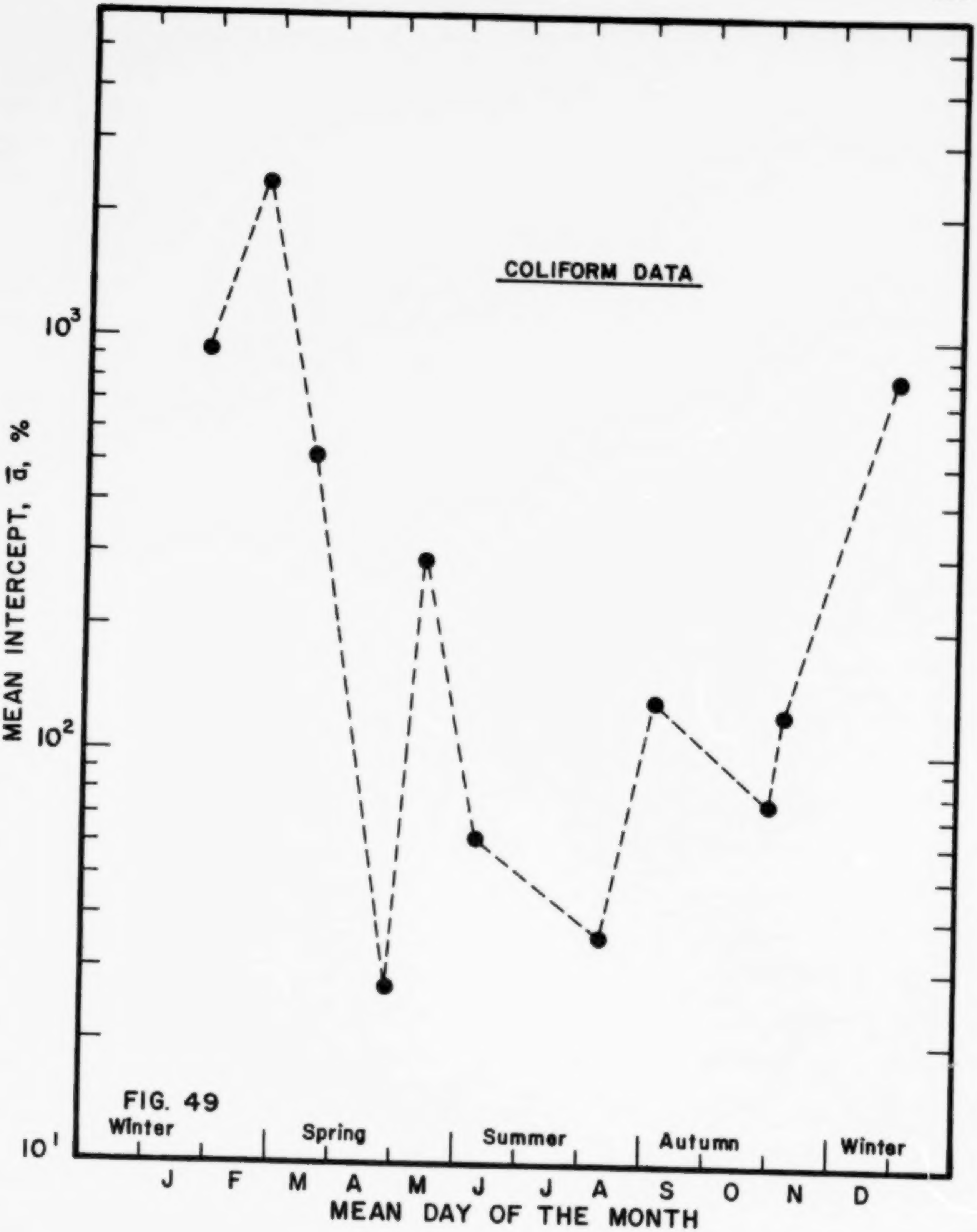

COLIFORM DATA
MEAN INTERCEPT, $\bar{a}$, %
10^3
10^2
10^1
Winter
Spring
Summer
Autumn
Winter
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

FIG. 49

the year and that minimum values of $\underline{a}$ were obtained during the spring and summer months.

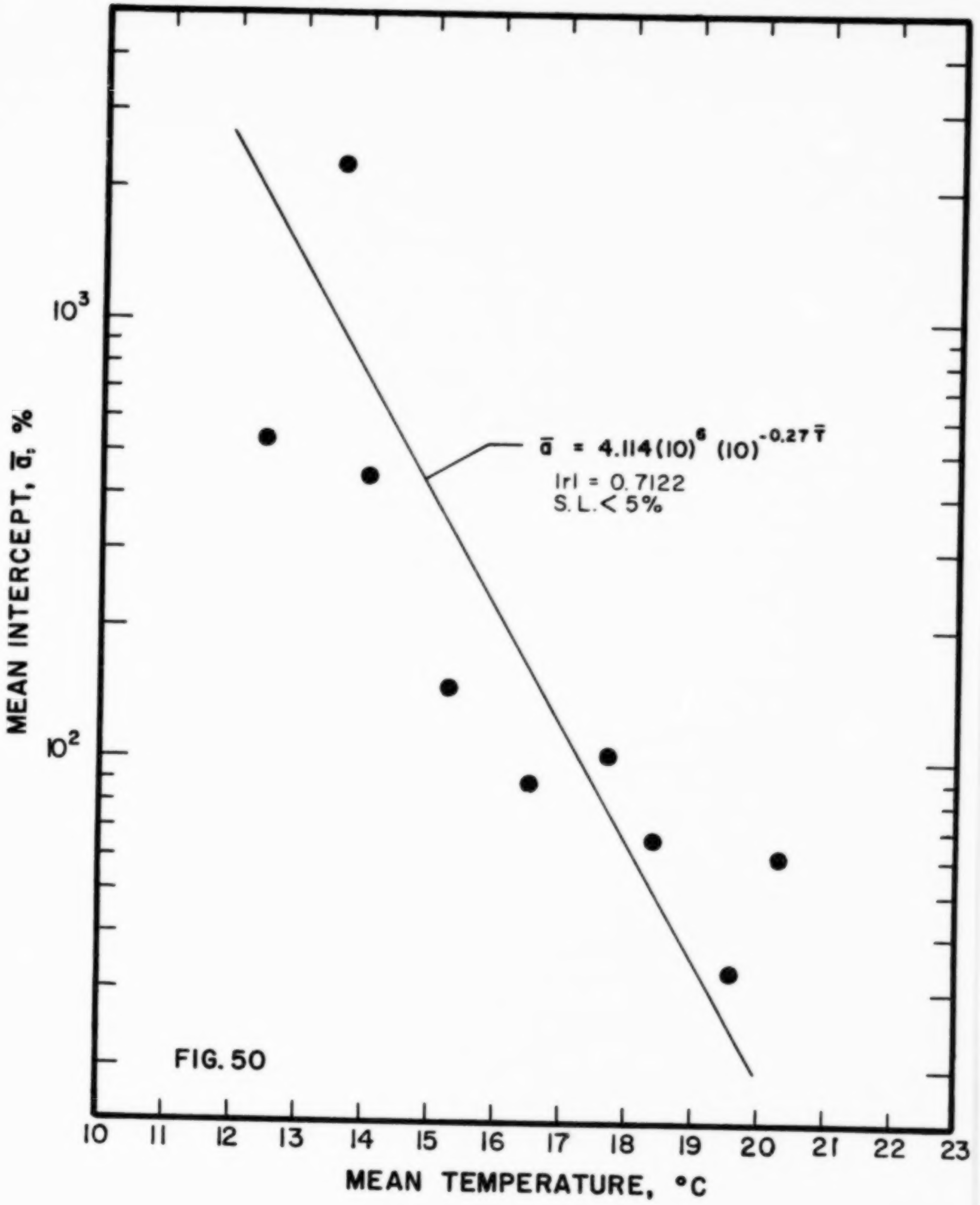
The data depicted in Figure 50 shows that a highly correlated linear relationship resulted when the log of mean $\underline{a}$ for each degree of temperature between 12 and 21° C. was plotted against the corresponding mean temperature. The trend is for $\underline{\bar{a}}$ to decrease with increasing $\bar{T}$.

As in the case of the initial slope of the coliform population curves, the intercept $\underline{a}$ also appeared to be related somewhat to the initial rate of dilution and initial coliform concentration as shown by the data presented in Figures 51 and 52. Although the trends are not well defined, the intercept $\underline{a}$ appeared to decrease with increasing initial rate of dilution and initial coliform concentration.

There is an obvious similarity between the relationships for $\underline{a}$ presented above and those for the initial slope of the population curves discussed previously. Consequently, the hypotheses presented earlier regarding the possible interrelationship between the initial growth-mortality trends and such environmental phenomena as antibacterial agents also apply to the observed trends for the intercept $\underline{\bar{a}}$.

From an engineering standpoint, the relationships like those shown in either Figure 48 or in Figure 50 can be used -- within limits-- to estimate mean values of $\underline{a}$.

From the graphical description of equation (6) presented in Figure 11, it can be shown that the constant K_2 is the log rate of change of the population difference or delta function.



$\bar{a} = 4.114(10)^6 (10)^{-0.27\bar{T}}$

$|r| = 0.7122$

S.L. < 5%

FIG. 50

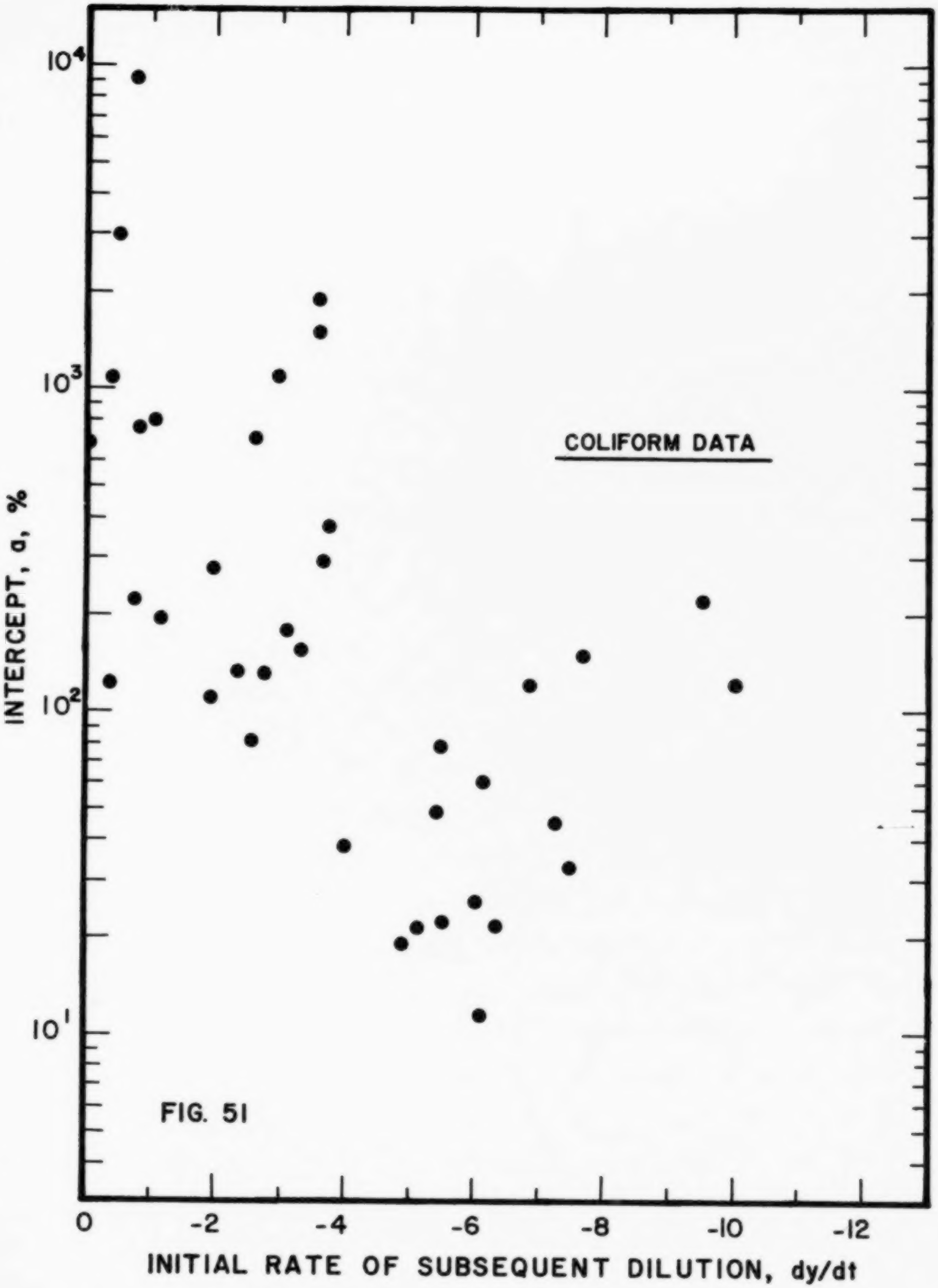

COLIFORM DATA
10^4
10^3
10^2
10^1
INTERCEPT, a, %
0
-2
-4
-6
-8
-10
-12
INITIAL RATE OF SUBSEQUENT DILUTION, dy/dt

FIG. 51

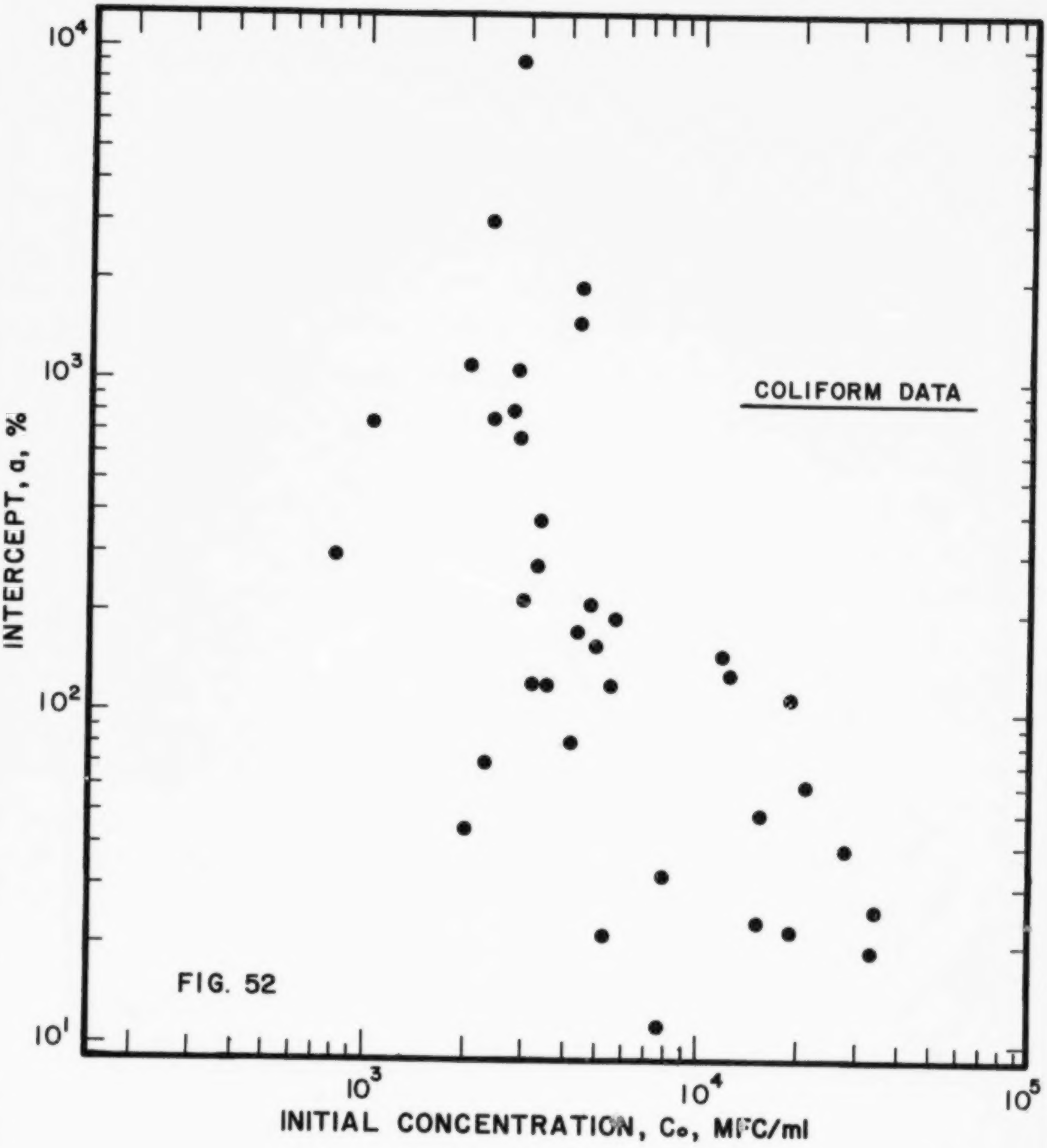

COLIFORM DATA
INTERCEPT, a, %
10^4
10^3
10^2
10^1
10^3
10^4
10^5
INITIAL CONCENTRATION, Co, MFC/ml

FIG. 52

Since the effect of K_2 is greatest relatively near the origin of a waste plume, the environmental factors assumed to influence the initial slope and intercept a would be assumed to exert a similar influence on K_2.

Figure 53 is a semi-log plot of mean $\overline{K}_2$ vs. mean day of the month. It is apparent from these data that $\overline{K}_2$ varied seasonally and that the maximum values obtained during the summer and fall months.

Figure 54 illustrates the relationship between mean K_2 and mean water surface temperature for temperatures ranging between 12 and 20° C. These data reflect the seasonal variation of both K_2 and temperature and show an apparent tendency for K_2 to increase with increased temperature.

Figures 55 and 56 show the relationship between the initial coliform density and initial rate of dilution and K_2. Although trend lines are not presented for these data, K_2 appears to increase with increasing initial coliform concentration and rate of dilution.

Like the initial slope and $\overline{a}$, it is difficult to develop definitive cause and effect relationships between K_2 and the environmental factors discussed herein. Practically speaking, however, temperature and season of the year appear to be key factors from which relevant estimates of mean K_2 can be made.

Mathematically speaking the parameter K_1 (or k_1) is the logarithmic rate of decrease of the linear segment of the bacterial population curves described in Figures 6 and 11. This segment corresponds to the section of a waste plume at distances $x > x_\Delta$, or equivalent drift (exposure) times $t > t_\Delta$, from the

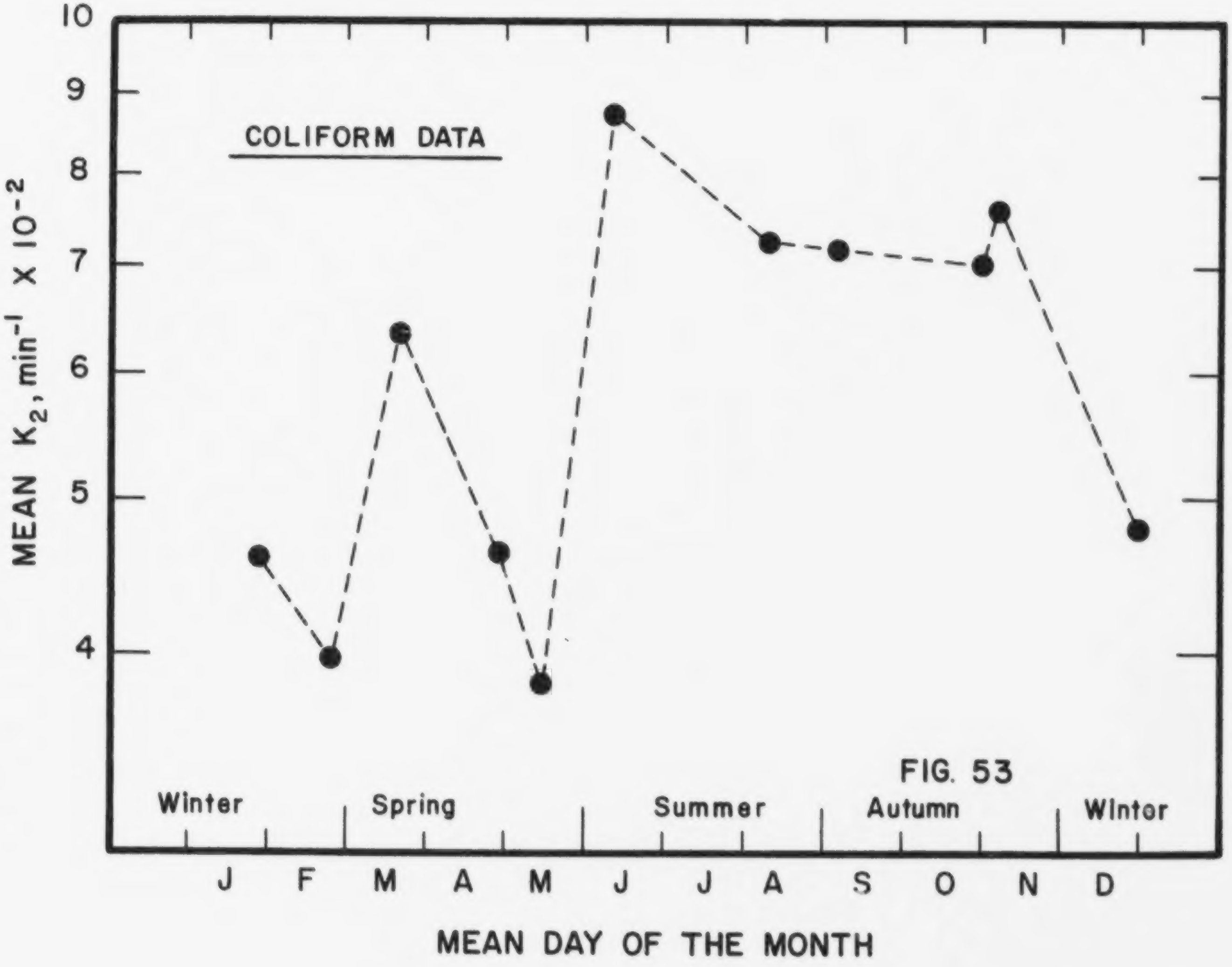

COLIFORM DATA
MEAN K_2, min^{-1} X 10^{-2}
10
9
8
7
6
5
4
Winter
Spring
Summer
Autumn
Wintor
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

FIG. 53

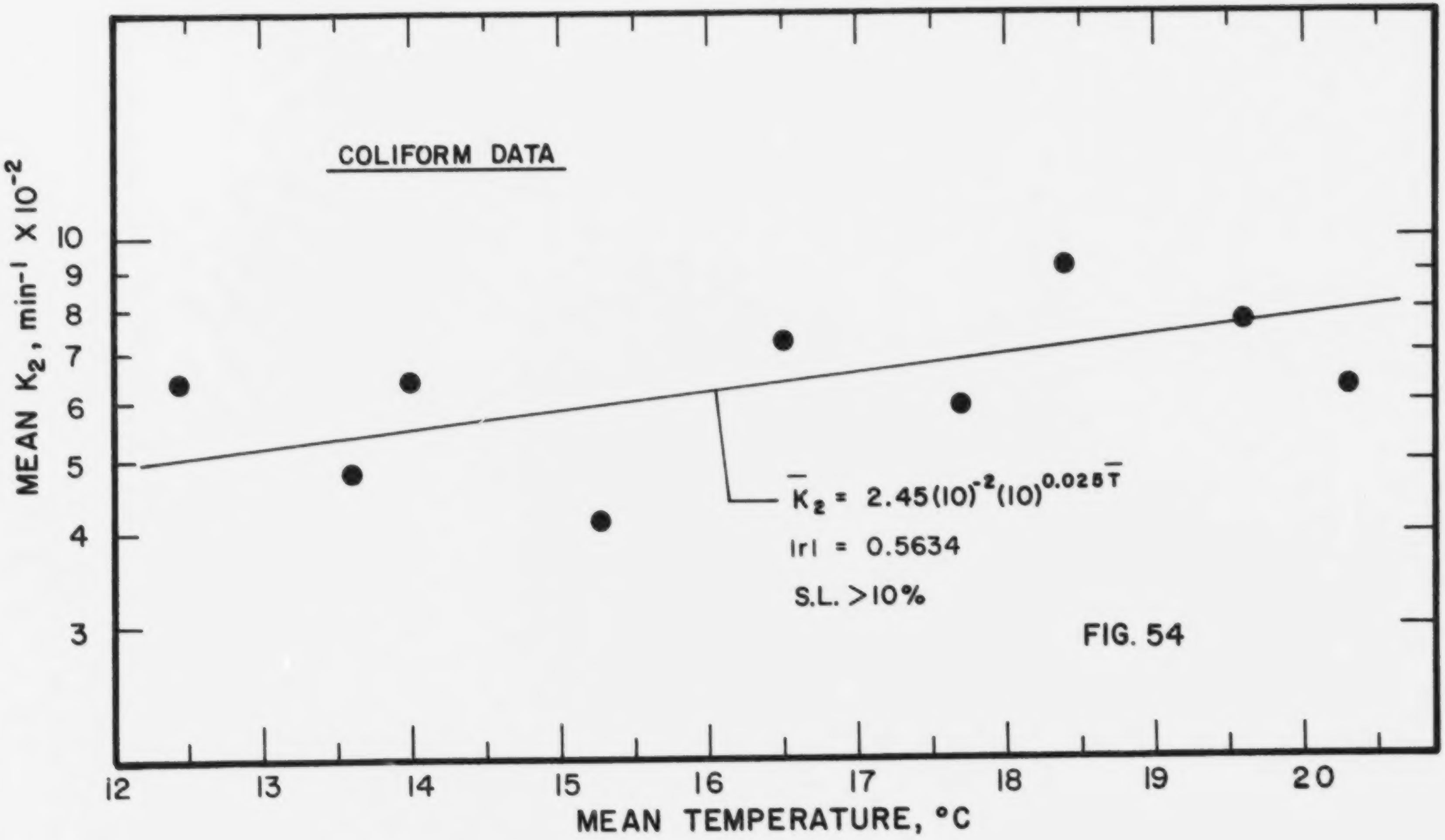
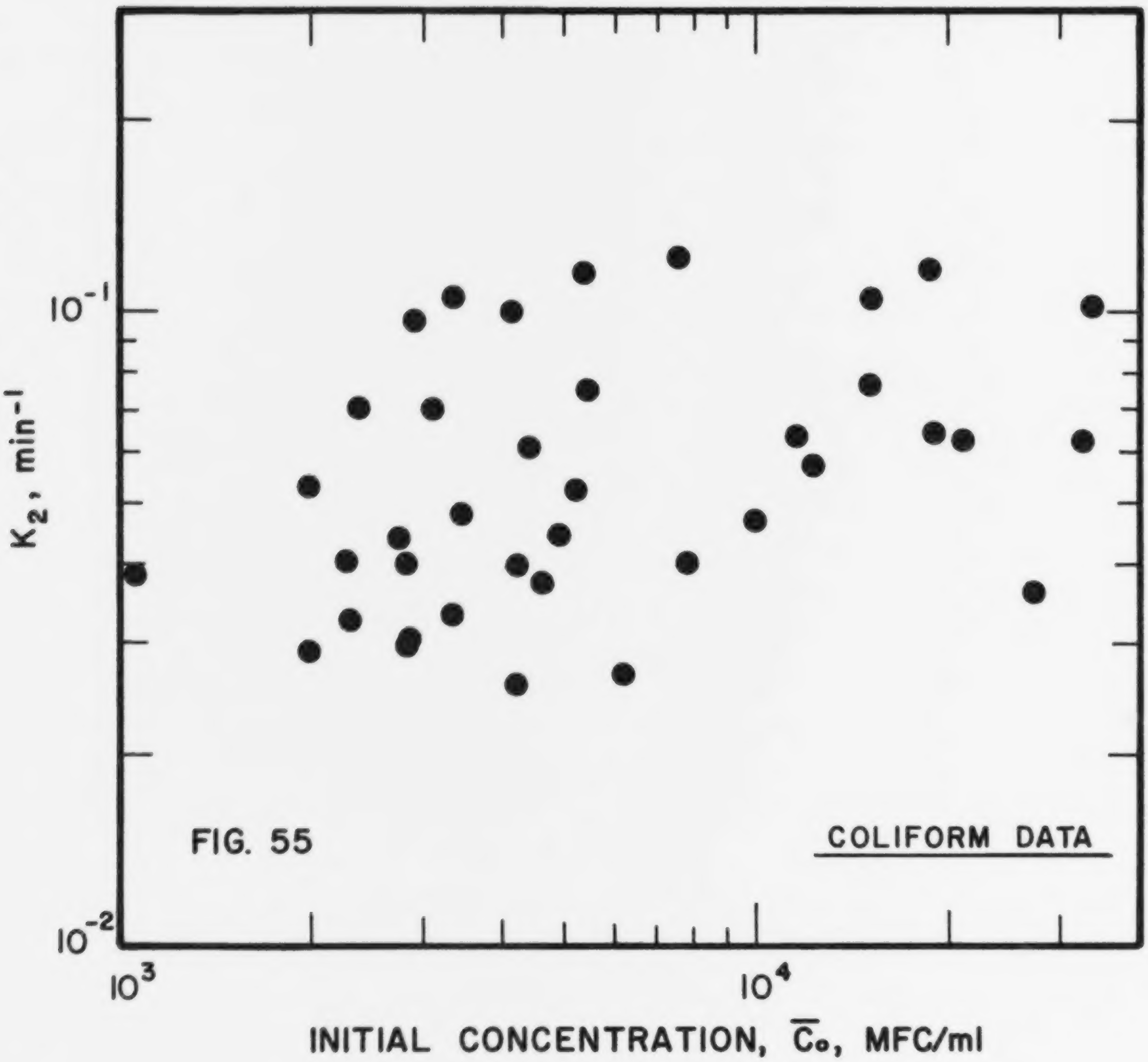

COLIFORM DATA
MEAN K₂, min⁻¹ X 10⁻²
10
9
8
7
6
5
4
3
12
13
14
15
16
17
18
19
20
MEAN TEMPERATURE, °C
$\bar{K}_2 = 2.45(10)^{-2}(10)^{0.025\bar{T}}$
$|r| = 0.5634$
S.L. >10%

FIG. 54



COLIFORM DATA
10^{-1}
10^{-2}
K_2, min-l
10^3
10^4
INITIAL CONCENTRATION, $\overline{C}_o$, MFC/ml

FIG. 55

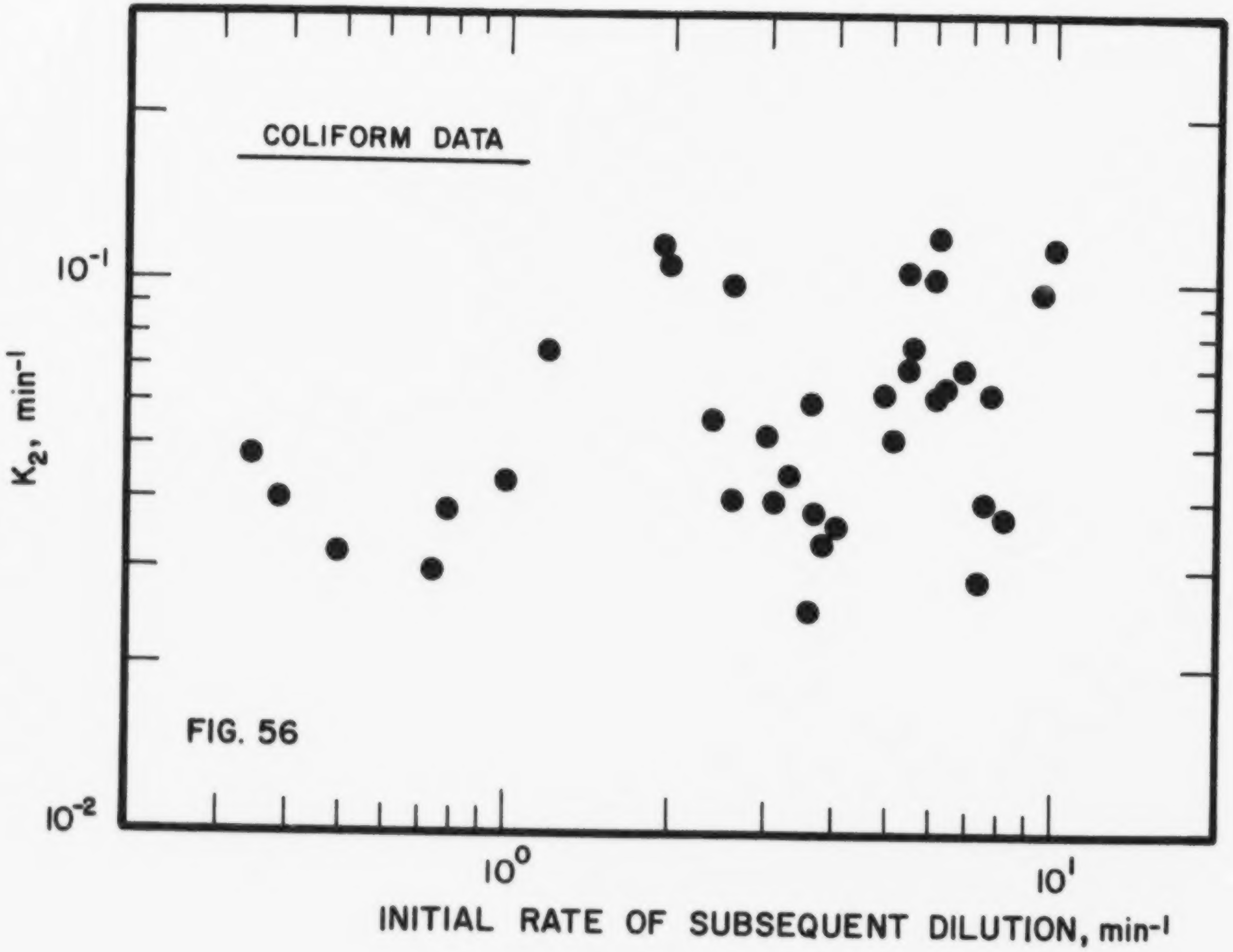

COLIFORM DATA
K_2, min^{-1}
10^{-1}
10^{-2}
10^0
10^1
INITIAL RATE OF SUBSEQUENT DILUTION, min^{-1}

FIG. 56

origin. In these experiments calculated values of t_Δ ranged from 15 to 235 minutes, and the average was 101 minutes. For exposure times of this magnitude the conditions existing at the origin of a waste plume would be expected to have little influence on the magnitude of K_1. It seemed reasonable, however, to assume that K_1 was related to those environmental factors producing relatively long-term effects on coliform mortality, that is, mortality at exposure times greater than t_Δ. Among these factors were assumed to be season of the year, water temperature, and in this case, gross solar radiation.

Figure 57 illustrates the relationship obtained when the log of mean K_1 was plotted against the corresponding mean day of the month. From these data it is evident that, unlike previous graphs of the other popuation parameters, there is a strong linear relationship between the variables. The fact that K_1 decreased steadily from a maximum value in January to a minimum in December appeared to indicate that the observed trend is not simply a reflection of the seasonal variation in water temperature. This can be seen from the relationship between the log of mean K_1 and mean water surface temperature as shown in Figure 58.

Attempts to assess the effect of gross solar radiation on the rate of coliform mortality were largely unsucessful. This was primarily due to the fact that in these experiments no consideration was given to the so-called dark reaction, that is, coliform die-away in the absence of light as described by Gameson and Saxon (1968). Assuming the dark reaction takes place simultaneously in the presence of light, it is necessary

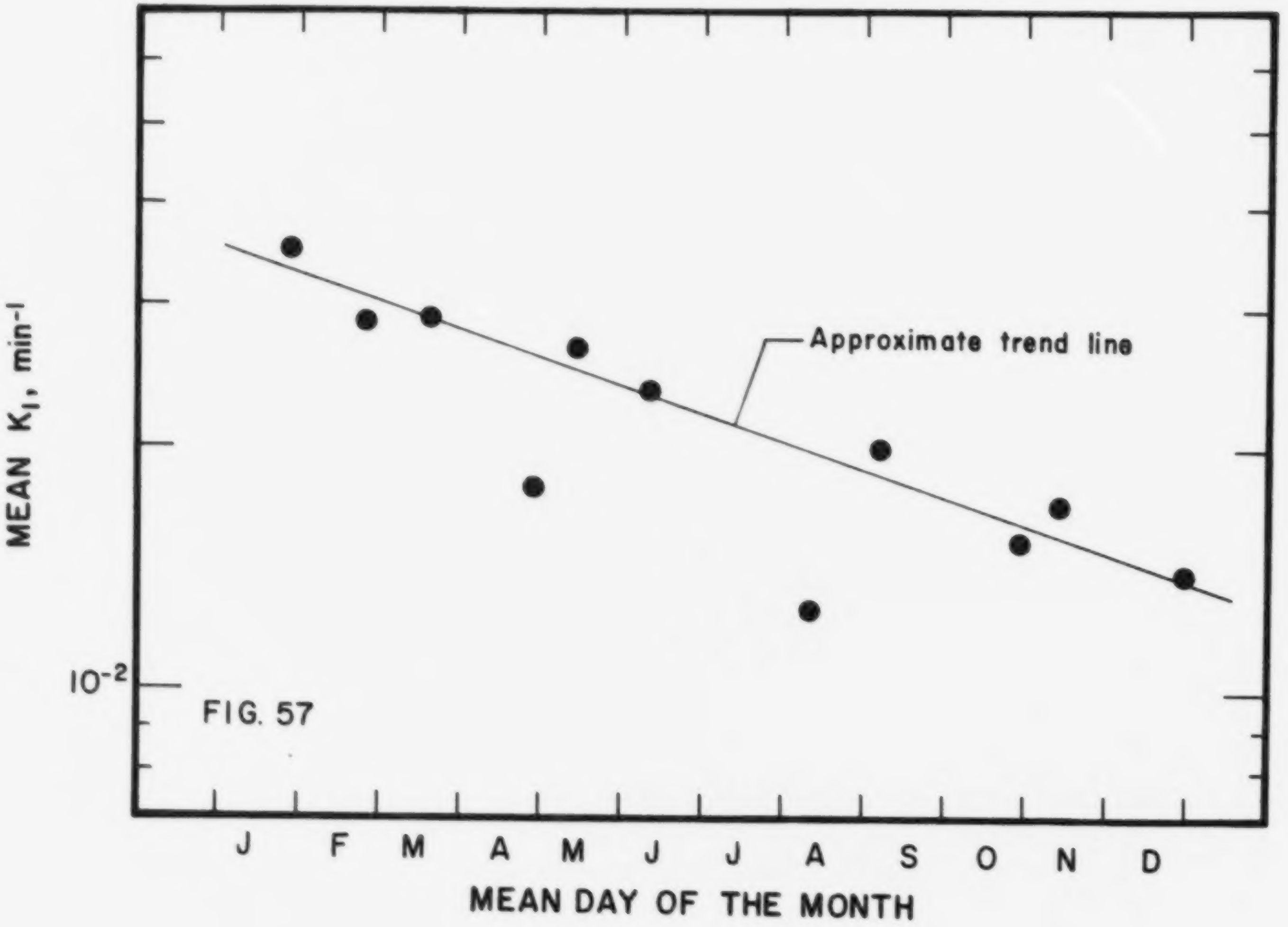


FIG. 57

Approximate trend line
MEAN K_1, min^{-1}
10^{-2}
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

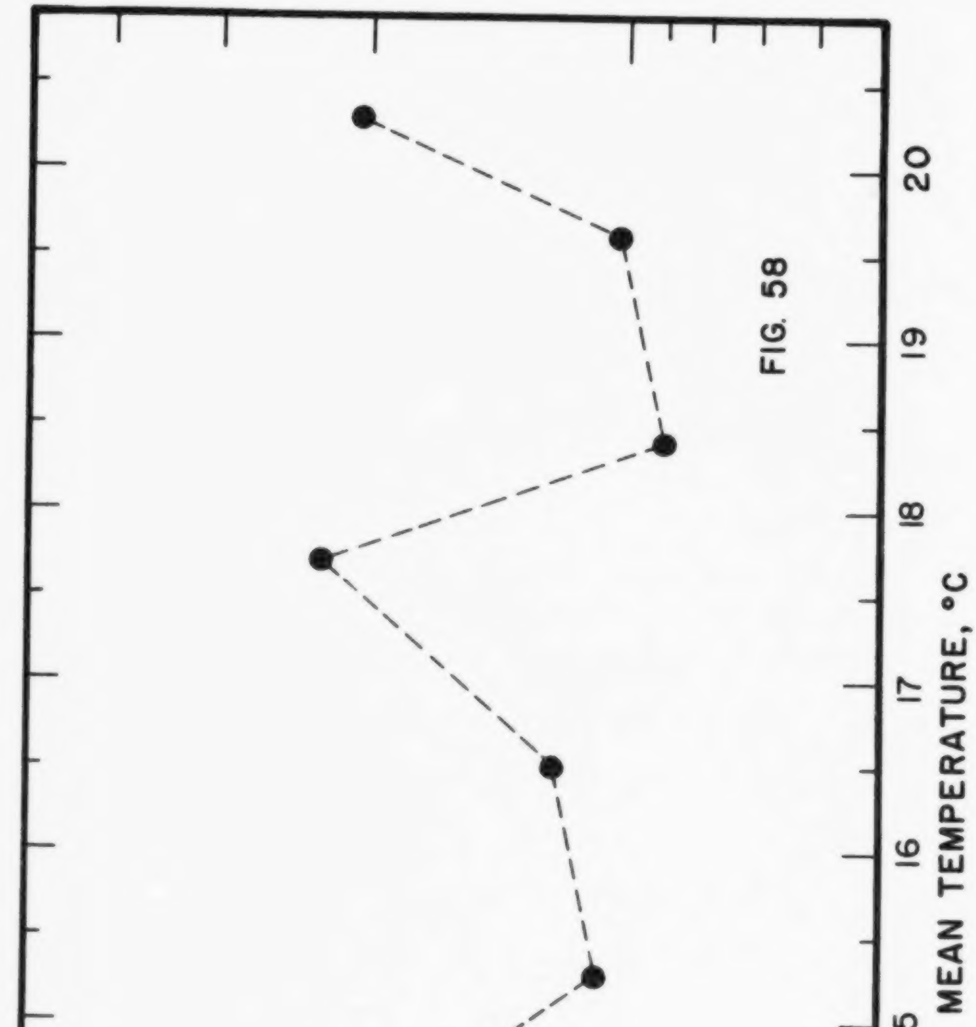

COLIFORM DATA
MEAN K$_1$, min^{-1} X 10^{-2}
1
2
3
4
MEAN TEMPERATURE, °C
12
13
14
15
16
17
18
19
20

FIG. 58

to correct for this effect in order to make a true assessment of the influence of gross solar radiation on coliform mortality.

By making the dubious assumption that in the present experiments the effect of the dark reaction was minimal, it was possible to make a crude assessment of the influence of gross solar radiation on coliform mortality. Since the bactericidal effects of solar radiation are known to be cumulative, it was necessary to determine the total gross radiation input at the water surface for the duration of each experiment. These data were obtained by calculating the appropriate area under the curves of time vs. rate of solar radiation input as obtained from a recording pyrheliometer mounted on the R.V. Velero IV; the results are shown in Table 3.

A semilog plot of mean K_1 vs. cumulative gross solar radiation for all experiments is shown in Figure 59. A visual inspection of these data indicates that little or no correlation existed between these variables. These results disagree with those obtained by Gameson and Saxon (1968) as discussed in a previous section of this report. This discrepency may well be due to neglecting the effect of the dark reaction when calculating values of K_1.

The above results indicate that there is a strong seasonal variation in the magnitude of the rate constant K_1 which appears to be relatively independent of water temperature. Practically speaking rough estimates of the magnitude of K_1 for use in design situations can be obtained from the data presented in Figure 57.

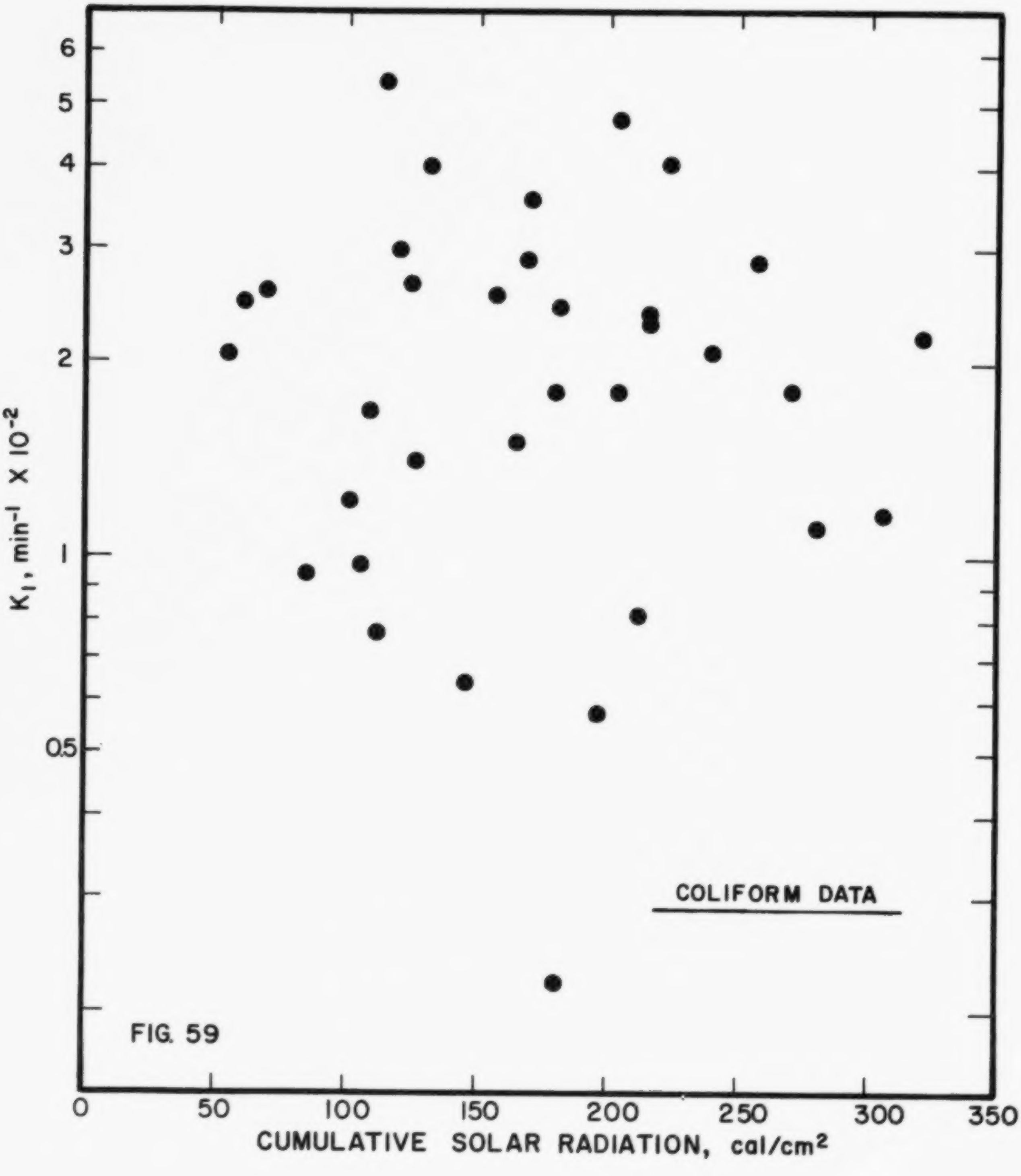

6
5
4
3
2
1
0.5
K_1, min^{-1} X 10^{-2}
COLIFORM DATA
0
50
100
150
200
250
300
350
CUMULATIVE SOLAR RADIATION, cal/cm^2

FIG. 59

As discussed in a previous section of this report it has become more or less traditional to use Chick's Law to describe the spatial or temporal distribution of coliform bacteria in waste fields dispersing in the ocean. Although the results of the present experiments indicate that in most cases Chick's Law does not accurately describe observed conditions, it is likely that the use of this equation will continue in the future. Consequently, values of the population parameter T_{90}, as defined by equation (2), are presented for future reference in Table 5.

It is of some interest to investigate the possible influence of such environmental factors as season of the year and water temperature on the observed values of T_{90}. Figure 60 illustrates the relationship obtained when the log of the mean values of T_{90} are plotted against corresponding mean day of the month. From these data it is evident that there was a slight tendency for minimum values of T_{90} to occur in the spring and summer months and maximum values to occur in the fall and early winter.

The relationship between the log of mean T_{90} and mean water temperature is shown in Figure 61. In this case there was a slight tendency for T_{90} to decrease with increasing temperature. This trend, like similar trends for the parameters a and K_2, is obviously related to the seasonal pattern described in Figure 60.

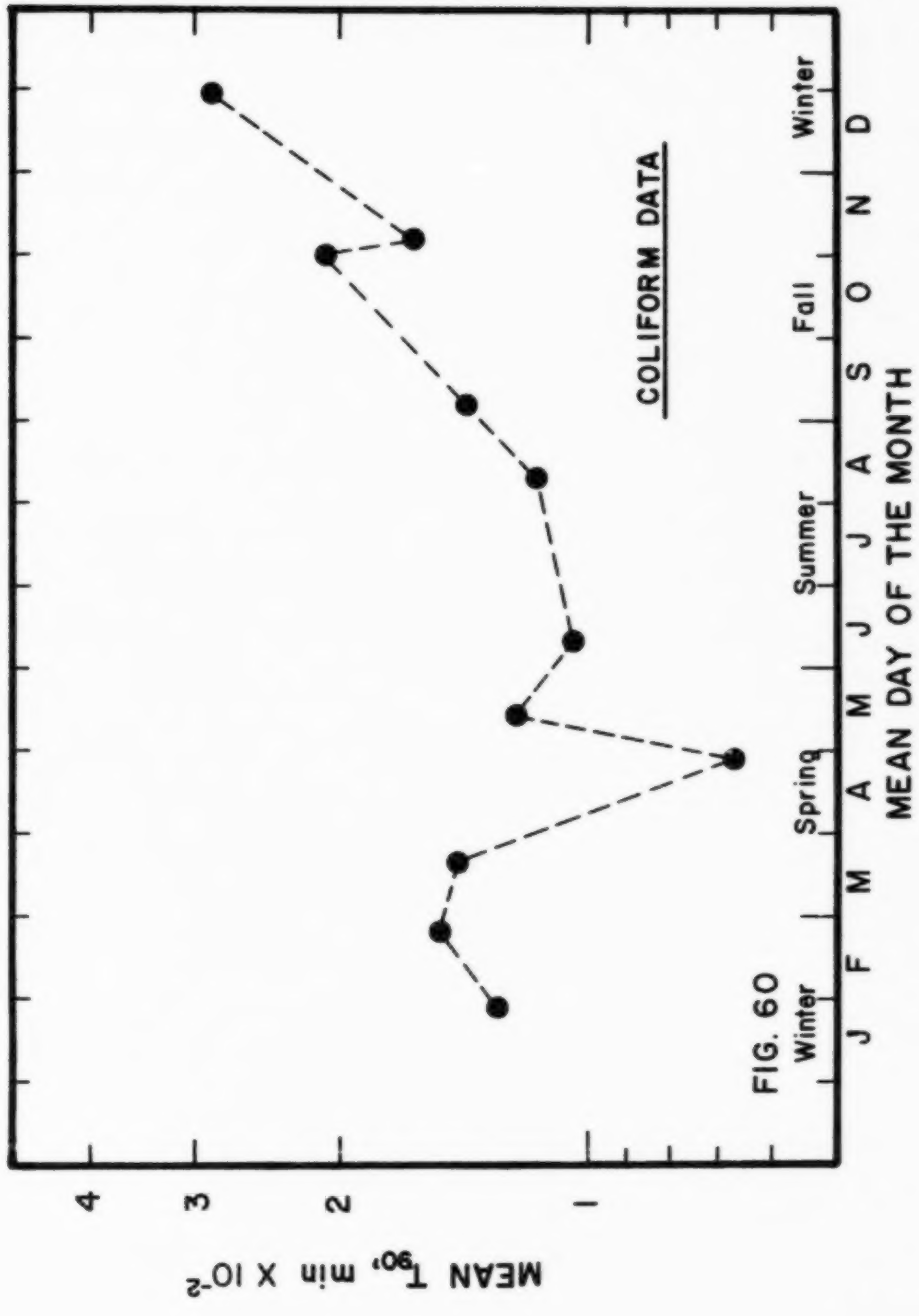


FIG. 60

COLIFORM DATA
MEAN T_{90}, min X 10^{-2}
1
2
3
4
MEAN DAY OF THE MONTH
J
F
M
A
M
J
J
A
S
O
N
D
Winter
Spring
Summer
Fall
Winter

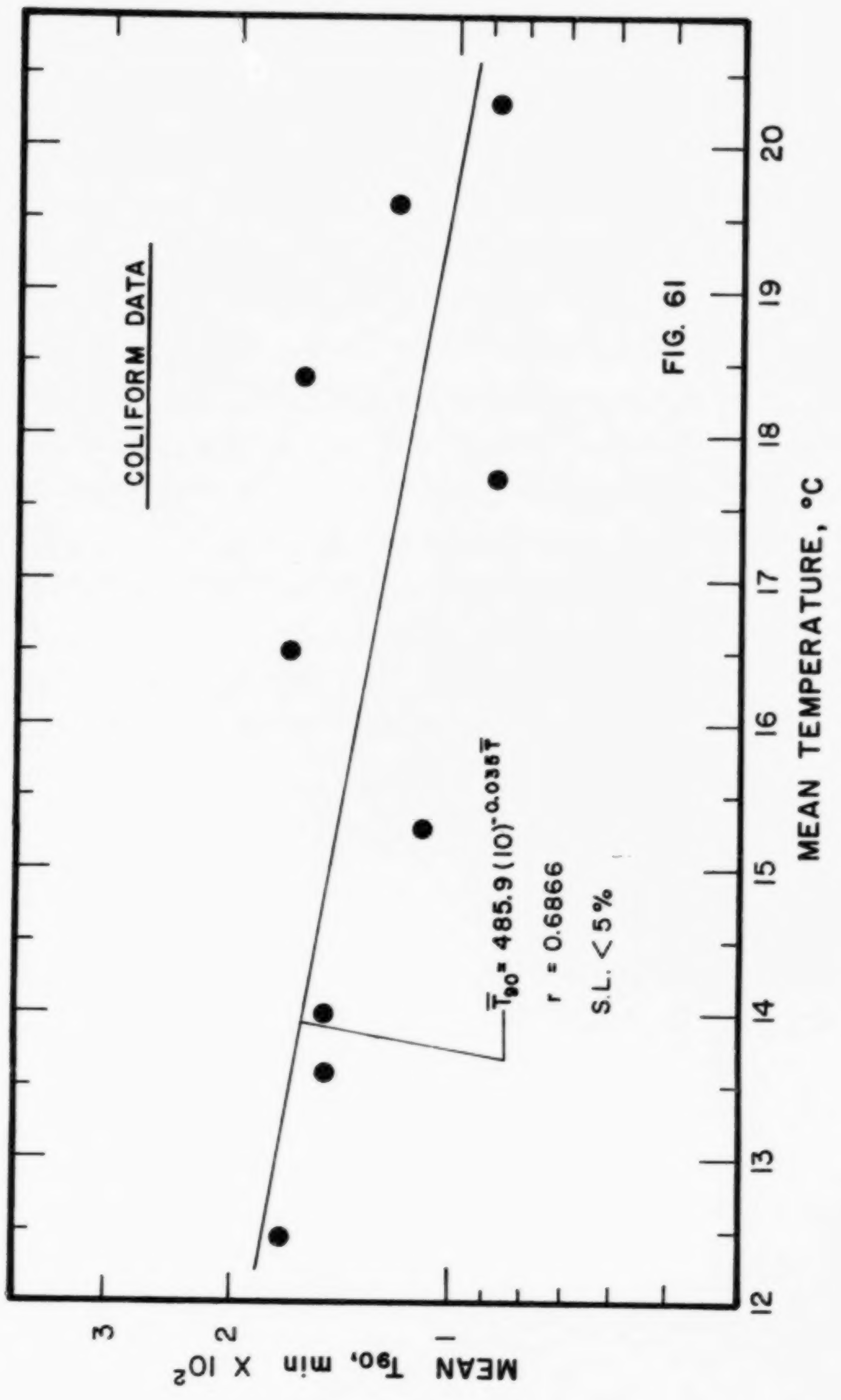

COLIFORM DATA
$\overline{T}_{90} = 485.9\,(10)^{-0.035\overline{T}}$
r = 0.6866
S.L. < 5%
MEAN TEMPERATURE, °C
12
13
14
15
16
17
18
19
20
MEAN T_{90}, min X 10^2
1
2
3

FIG. 61

Experimental Results - Fecal Streptococci

The results of the field experiments pertaining to the dispersion of fecal streptococci were discussed in an earlier section of this report. It may be recalled that the following observations concerning this bacteriological group were made at that time:

1. The observed concentrations of fecal streptococci were from one to two orders of magnitude less than those of the coliform organisms.
2. Although in some experiments fecal streptococci tended to grow near the origin of the waste plumes, the initial rate of growth was much less than that for coliform bacteria.
3. The growth-mortality characteristics of fecal streptococci in surface waste fields in the ocean can be accurately described by equations (3) or (6).
4. The phenomenon of bacterial aftergrowth in the downstream portions of a surface plume was observed in some experiemnts involving the dispersion of fecal streptococci. Aftergrowth of coliform organisms did not occur.

In light of the last observation it was tentatively concluded that fecal streptococci may be a poor indicator of bacterial pollution in the ocean. This conclusion was based on the assumption that bacterial pathogens present in waste waters follows the same general growth-mortality trends as coliform bacteria. This assumption needs to be tested by controlled field experiments involving the simultaneous detection and enumeration of water borne pathogens and various indicator systems. It may be that fecal streptococci rather than coliform organisms follow more closely the actual growth-mortality characteristics of pathogens.

Since equations (3) and (6) were found to be applicable to the observed fecal streptococal growth-mortality patterns, an attempt was made to establish relationships between the population parameters for these equations and key environmental factors. A similiar attempt was made to assess the influence of the enviroment on the observed tendency for immediate growth or mortality of these organisms.

Initial Rate of Change. The tendency for fecal streptococci to grow near the origin of a surface plume was observed in several experiments. This tendency was not as pronounced or as predictable as that for organisms of the coliform group. This can be seen, for example, by the data presented in Figures 62 and 63, in which the mean initial rate of change is plotted against corresponding mean dav of the month and mean water temperature for both indicator systems. Although the data from the experiments involving fecal streptococci are relatively few, it is apparent that for the oceanic areas around the Ventura and Santa Barbara outfalls the initial slope varied little with season of the year or water temperature.

Similiar results were obtained when mean values of $(dy/dt)_0$ were plotted against initial fecal streptococcus concentration and initial rate of subsequent dilution.

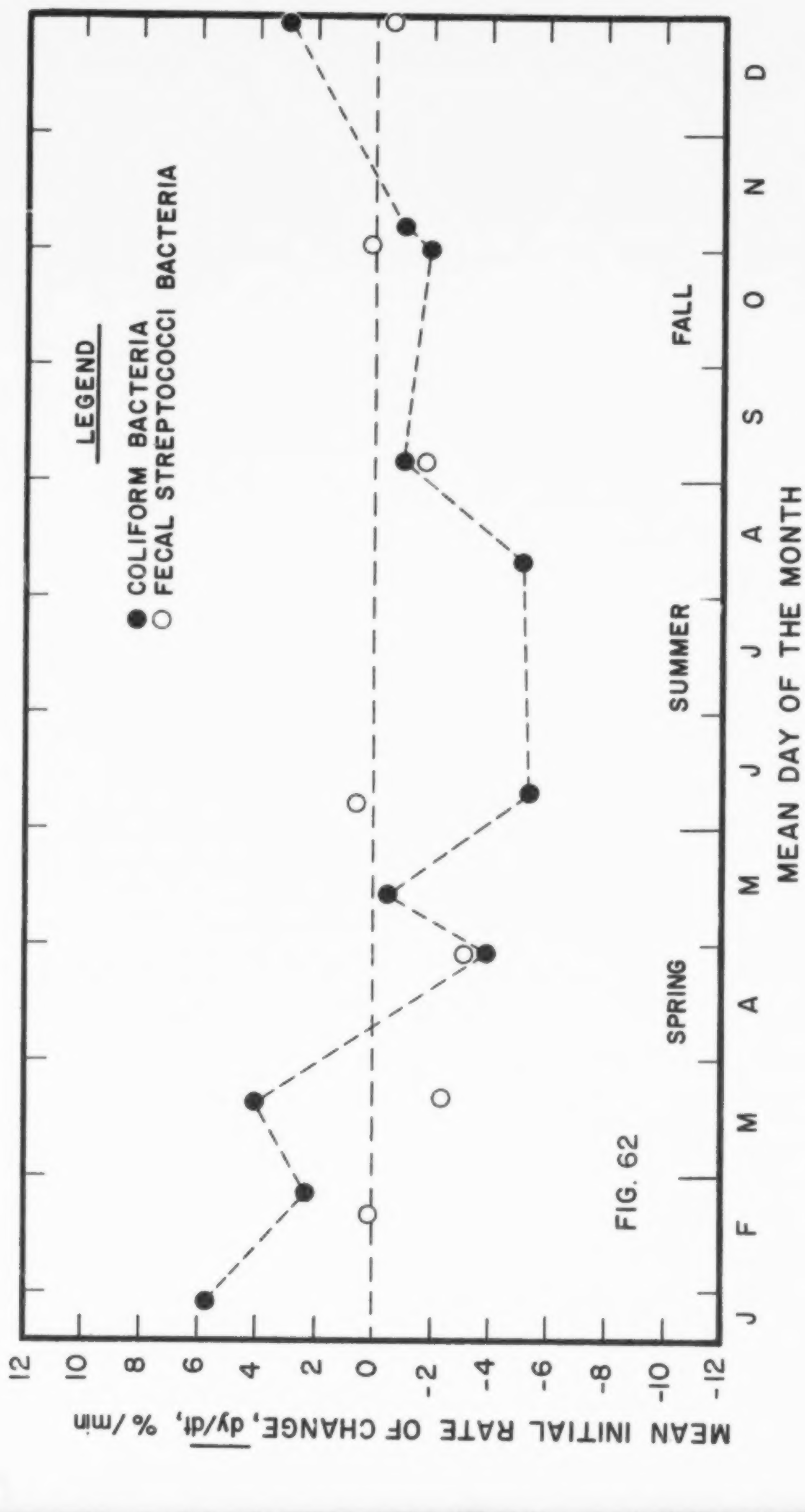


FIG. 62

LEGEND
● COLIFORM BACTERIA
○ FECAL STREPTOCOCCI BACTERIA
SPRING
SUMMER
FALL
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
MEAN INITIAL RATE OF CHANGE, dy/dt, %/min

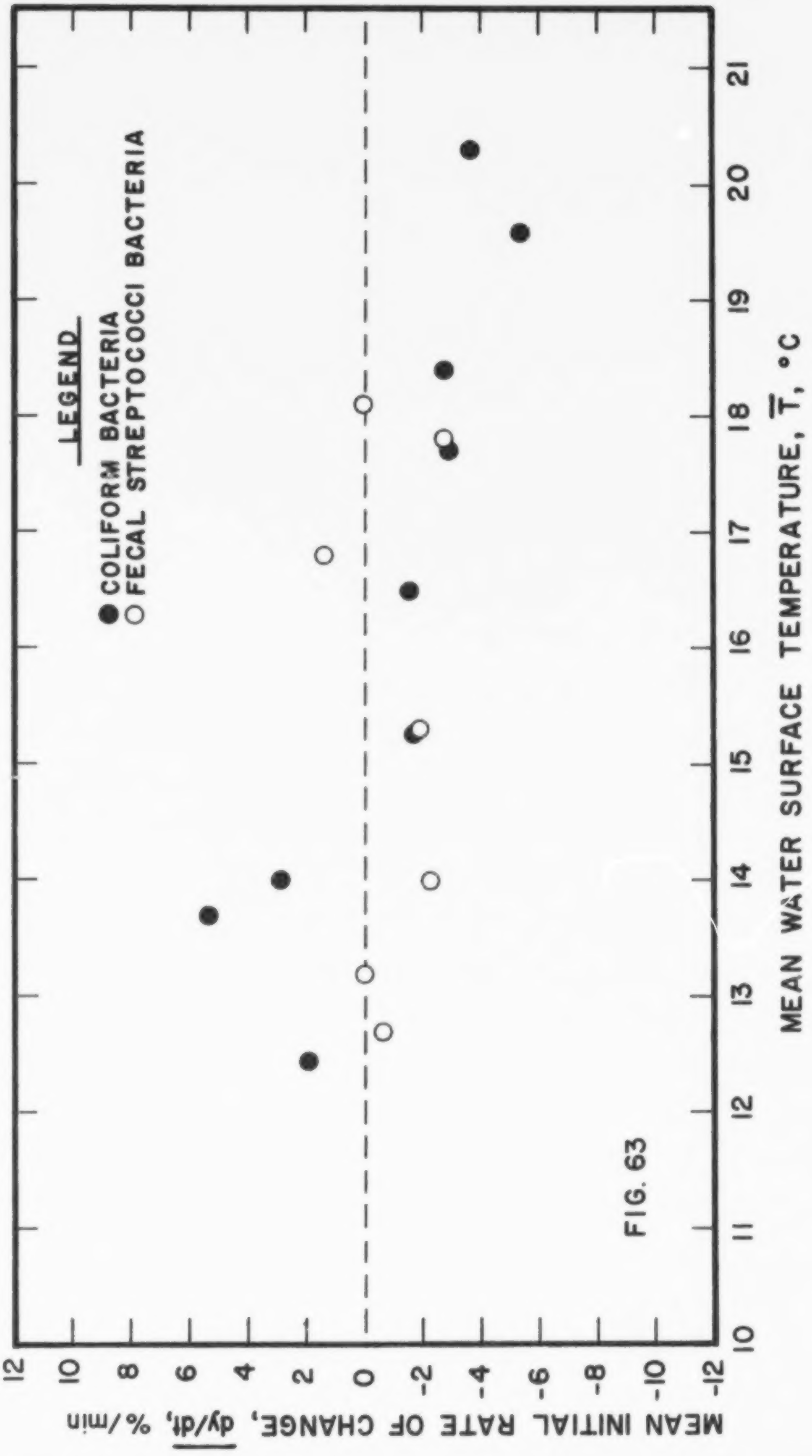

LEGEND
● COLIFORM BACTERIA
○ FECAL STREPTOCOCCI BACTERIA
MEAN INITIAL RATE OF CHANGE, dy/dt, %/min
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
MEAN WATER SURFACE TEMPERATURE, $\overline{T}$, °C
10
11
12
13
14
15
16
17
18
19
20
21

FIG. 63

It is difficult to explain why an apparent seasonal variation of $(dy/dt)_0$ occurred for one group of indicator bacteria but not the other. It is quite possible that a seasonal variation of the initial slope does occur for the fecal streptococcus group and that data presented herein were too few to establish this fact.

Population Parameters.

The relationship between the initial slope of the bacterial concentration curves and the intercept a is shown for both coliforms and fecal streptococci in Figure 64. It is evident from these data that there was a strong tendency for a to increase with an increasingly positive initial slope for both indicator groups. Hence the relationships between the initial slope and environmental factors discussed in the previous section would be expected to hold for the intercept $\bar{a}$. That this was the case is demonstrated by the data presented in Figures 65 and 66. Although it was difficult to draw any firm conclusions from these data, it appeared that the mean value of a varied relatively little with season of the year or mean water temperature.

The relationship between the mean rate constant $\bar{K}_2$ and season of the year for both indicator systems is shown in Figure 67. From these data it is apparent that the majority of the plotted points for fecal streptococci agree with those for the coliform bacteria. Until additional experimental evidence is obtained to show otherwise, it may be safe to conclude that the rate constants for the two indicator groups are of the same order of magnitude and follow similar seasonal patterns.

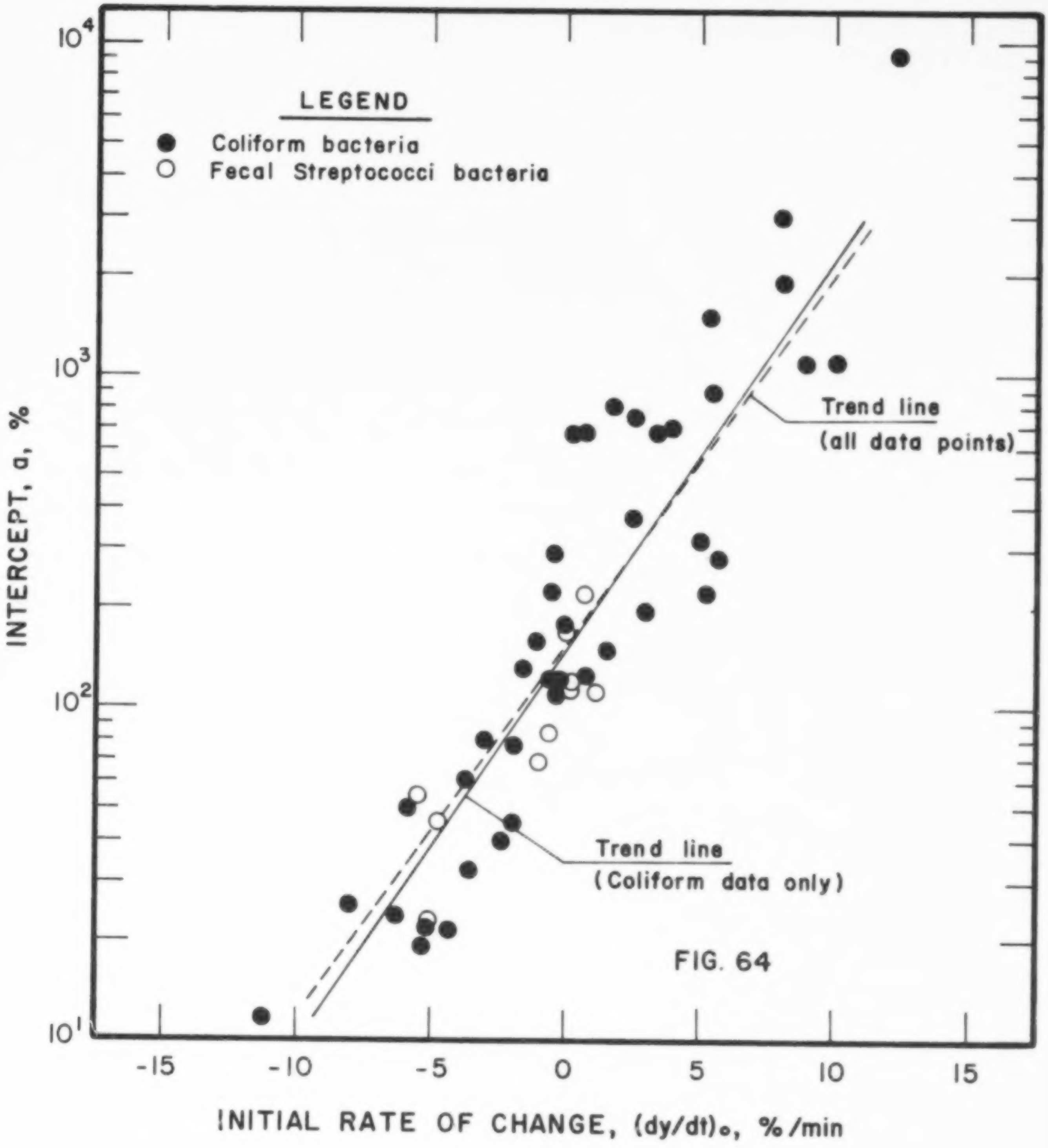

LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
Trend line
(all data points)
Trend line
(Coliform data only)
INTERCEPT, a, %
10^4
10^3
10^2
10^1
-15
-10
-5
0
5
10
15
INITIAL RATE OF CHANGE, $(dy/dt)_o$, %/min

FIG. 64

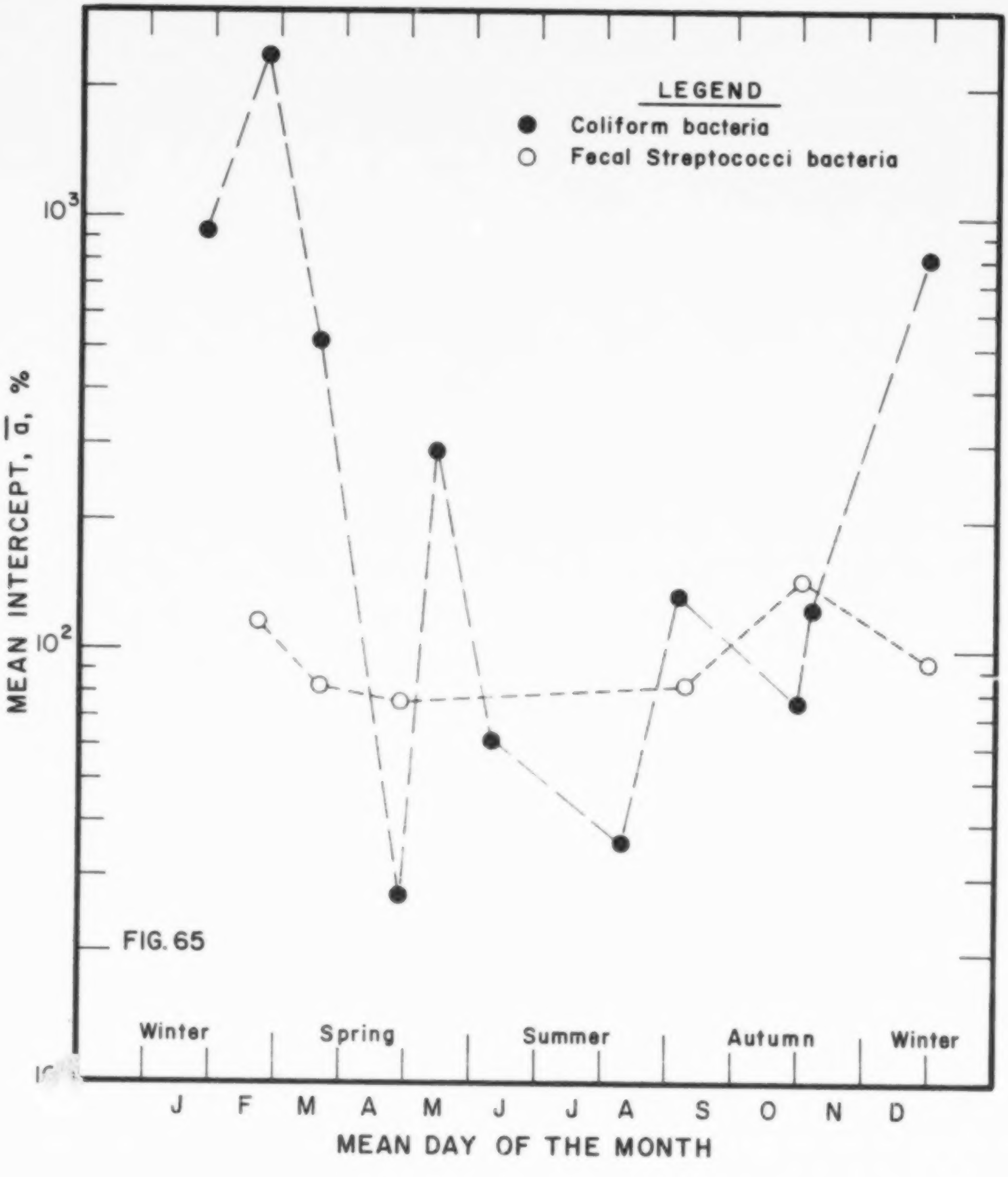

LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
MEAN INTERCEPT, ā, %
10^3
10^2
10^1
Winter
Spring
Summer
Autumn
Winter
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

FIG. 65

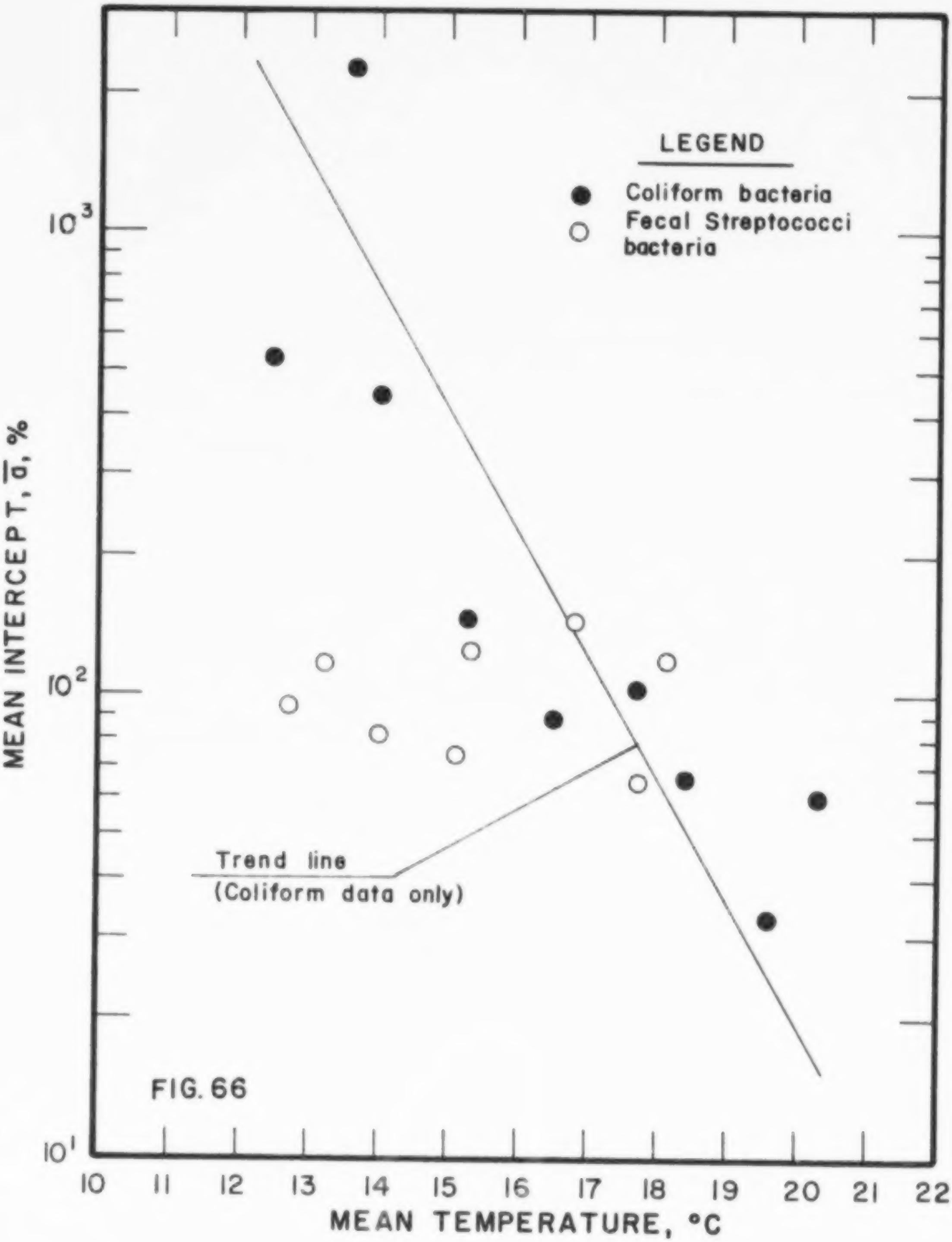

LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
Trend line (Coliform data only)
MEAN INTERCEPT, $\bar{a}$, %
10^3
10^2
10^1
MEAN TEMPERATURE, °C
10
11
12
13
14
15
16
17
18
19
20
21
22

FIG. 66

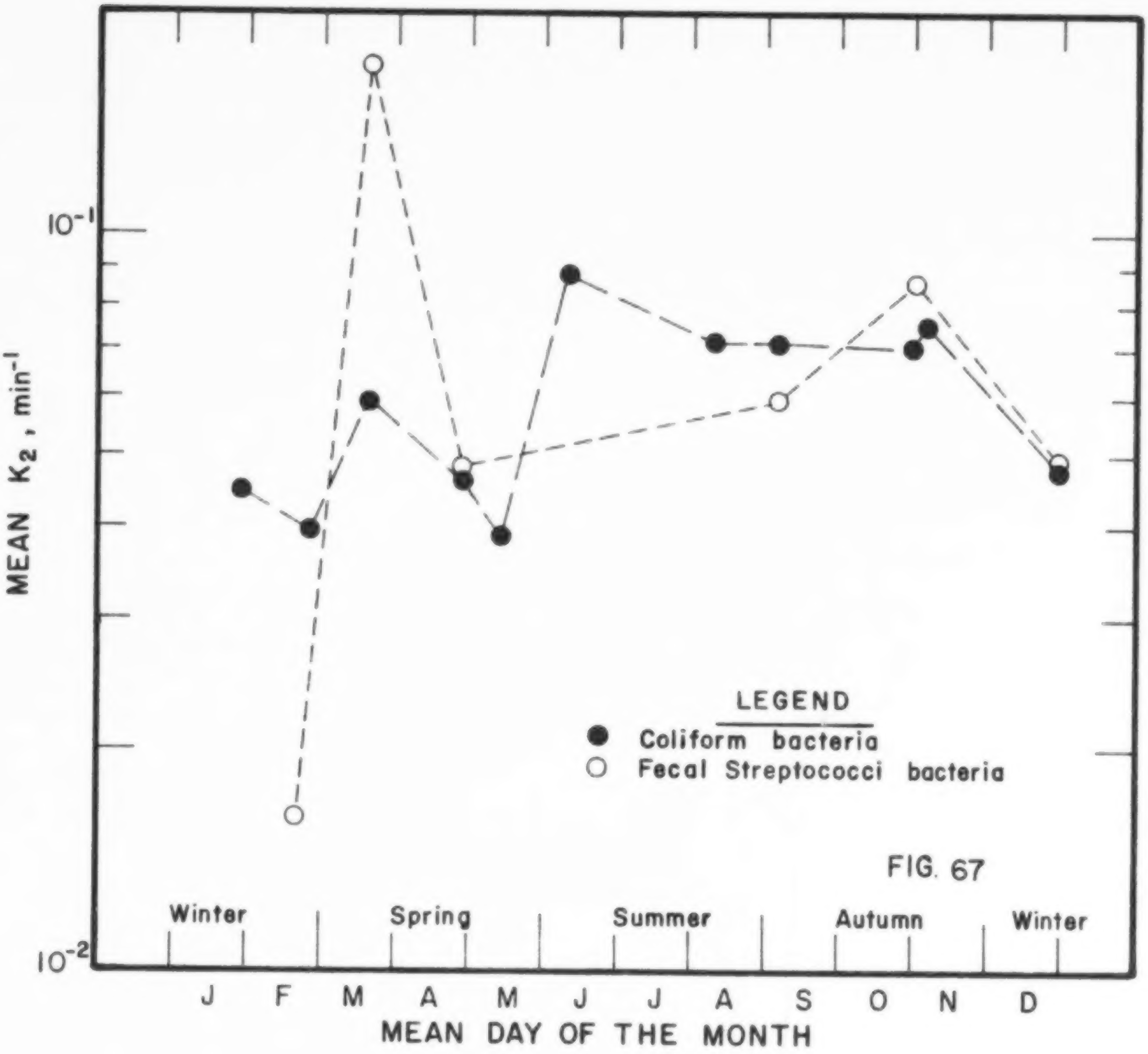

MEAN K_2, min^{-1}
10^{-1}
10^{-2}
LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
Winter
Spring
Summer
Autumn
Winter
J F M A M J J A S O N D
MEAN DAY OF THE MONTH

FIG. 67

The data presented in Figure 68 depicts the relationship obtained when the mean value of K_2 is plotted against corresponding mean water temperature. Again it is evident that with the exception of two of the data points for fecal streptococci, the two sets of data are in close agreement. Taking the data as a whole it is apparent that $\overline{K_2}$ tended to increase slightly with increased water temperature.

It is difficult to assess the influence of such factors as temperature or season of the year on the rate constant K_1. This is due to the fact that K_1 can be either a positive or negative number depending on the growth-mortality characteristics of the particular indicator system. As discussed previously, the phenomenon of aftergrowth of fecal streptococci occurred on several occasions; in these particular experiments the sign on the K_1t exponential term was positive indicating regrowth in the downstream segment of the waste plume. In other experiments there was no apparent aftergrowth and the sign on the K_1t exponential term was negative. Although insufficient data was obtained to establish why an apparent aftergrowth of fecal streptococci occurred during one experiment and not another, this tendency was apparently not related to season or water temperature. This can be seen by referring to the data presented in Tables 3 and 6 from which it is evident that positive value of K_1 occurred during the four seasons of the year and at various water temperatures.

Figures 69 and 70 illustrate the relationship between the mean value of K_1 and corresponding mean date and temperature for both indicator groups.

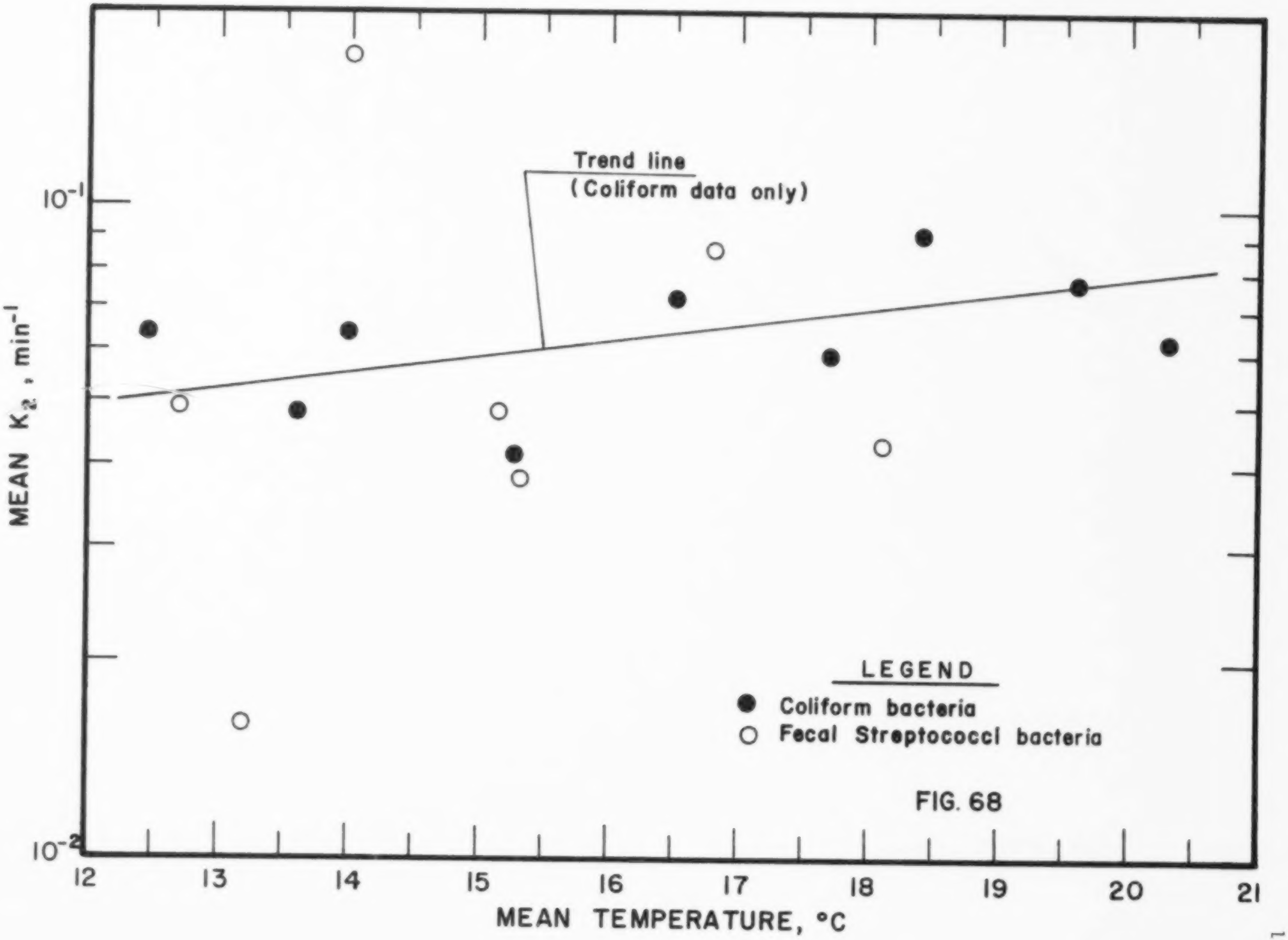

Trend line
(Coliform data only)
10^{-1}
10^{-2}
MEAN K_2, min^{-1}
12
13
14
15
16
17
18
19
20
21
MEAN TEMPERATURE, °C
LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria

FIG. 68

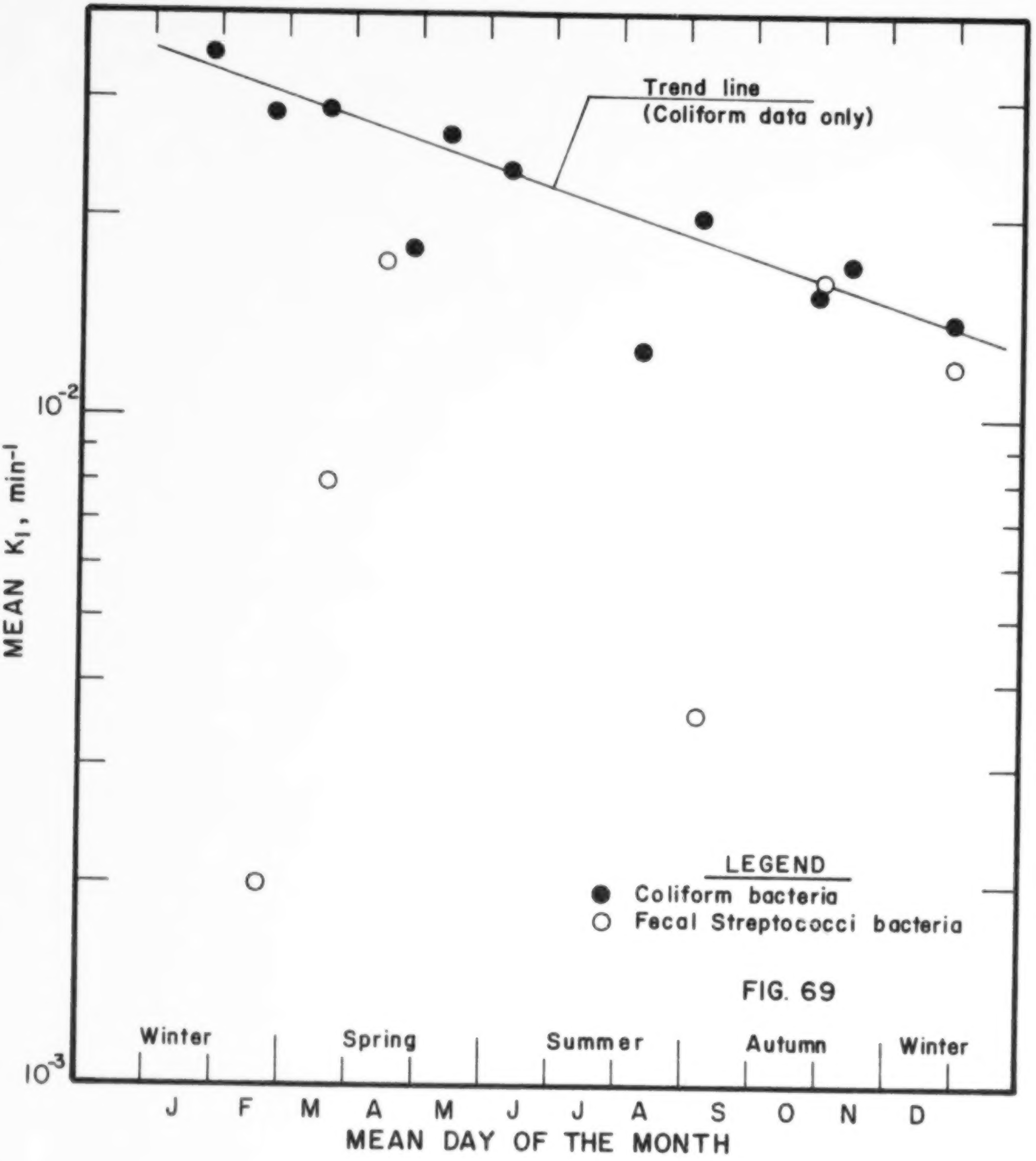

Trend line
(Coliform data only)
MEAN K_1, min^{-1}
10^{-2}
10^{-3}
LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
Winter
Spring
Summer
Autumn
Winter
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH

FIG. 69

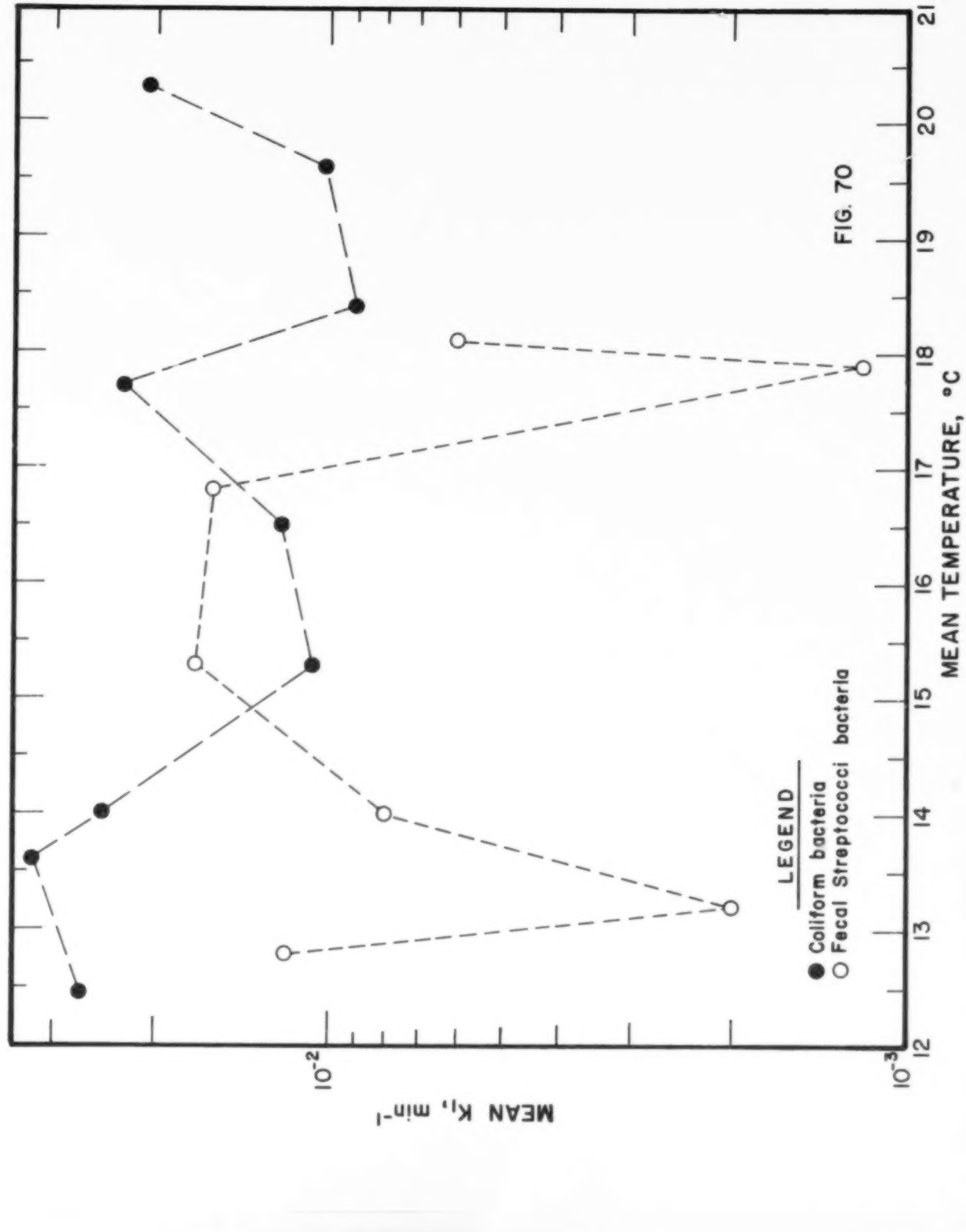


FIG. 70

LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria
MEAN TEMPERATURE, °C
12
13
14
15
16
17
18
19
20
21
MEAN K_1, min^{-1}
10^{-3}
10^{-2}

Although the data from the later experiments were relatively few in number, a comparison of the data for the two bacteriological groups, appears to show that mean values of K_1 for fecal streptococci are not related to the season of the year or temperature. These results disagree with those obtained for the coliform group which showed a strong tendency for K_1 to decrease from January to December.

The data presented in Figures 71 and 72 show the relationships obtained when mean values of T_{90} were plotted against mean day of the month and mean water temperature for both indicator systems. As in the case of the other population parameters, $\overline{T_{90}}$ for the fecal streptococcal group did not appear to be related to season of the year or temperature.

Discussion. It is obvious from the foregoing data presentations that the population parameters pertaining to the growth-mortality characteristics of fecal streptococci are highly unpredictable, this is particularly true for the rate constant $\overline{K_1}$. These results, although derived from rather meager experimental data, appear to indicate that this particular indicator group is of limited practical value in the design of marine waste outfall systems. As mentioned previously, this somewhat tenuous conclusion is based on the assumption that the growth-mortality patterns of bacteria of the coliform group are similar to those of enteric pathogenic bacteria. Although there is little epedimiological evidence to indicate the assumption is not valid, further research is needed on this subject.

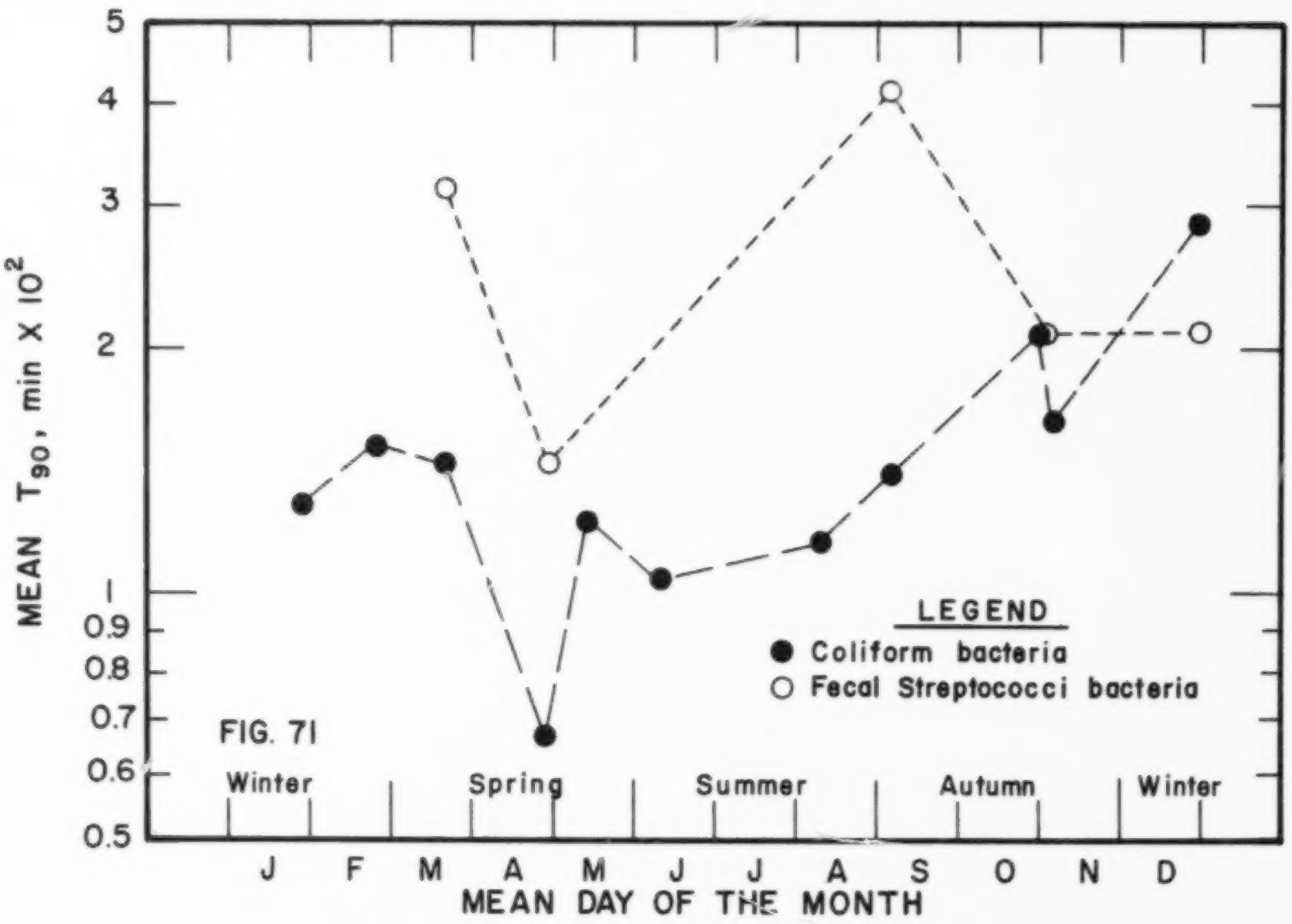


FIG. 71

MEAN T_{90}, min X 10^2
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
Winter
Spring
Summer
Autumn
Winter
J
F
M
A
M
J
J
A
S
O
N
D
MEAN DAY OF THE MONTH
LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria

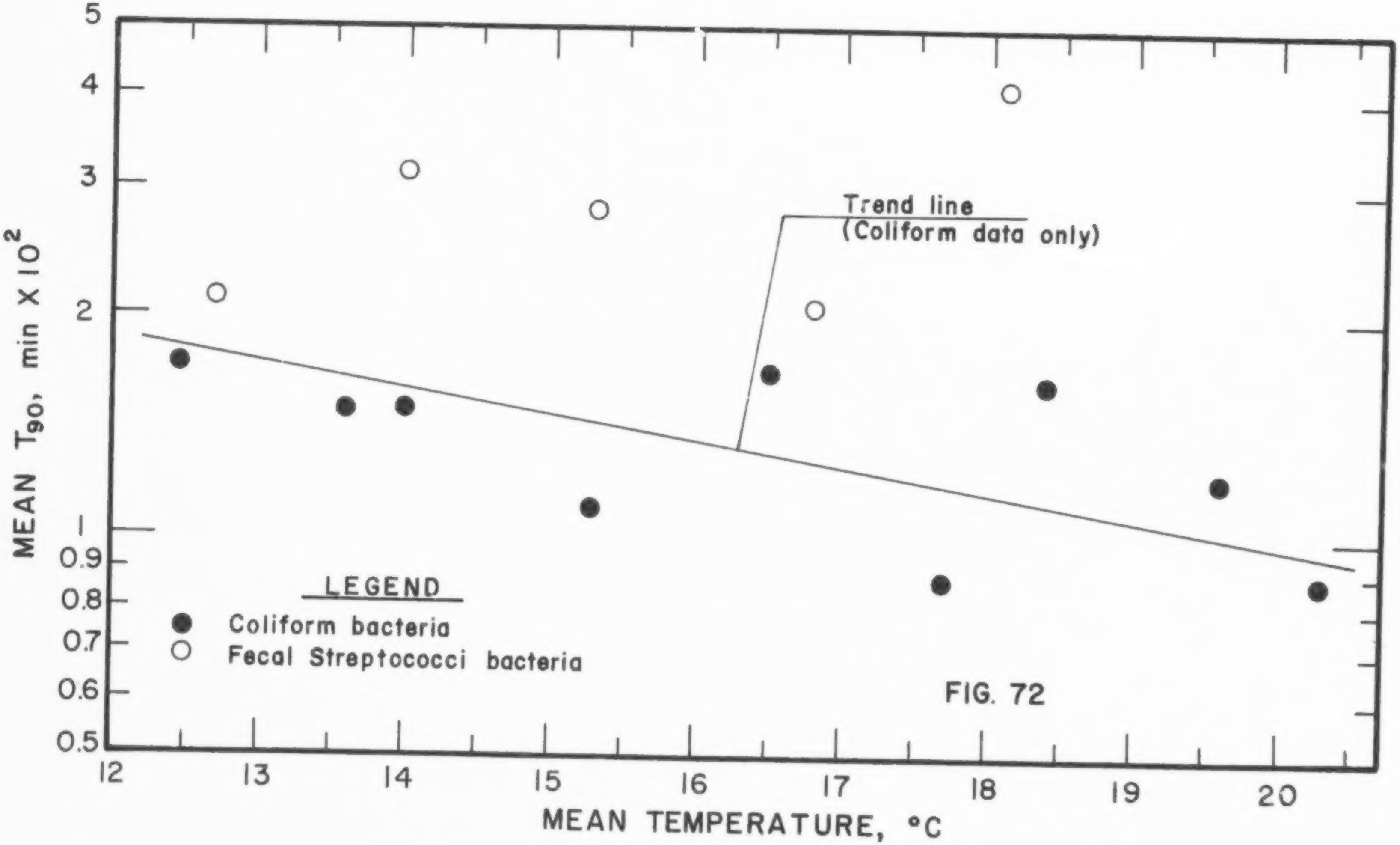

MEAN T_{90}, min X 10^2
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
12
13
14
15
16
17
18
19
20
MEAN TEMPERATURE, °C
Trend line
(Coliform data only)
LEGEND
● Coliform bacteria
○ Fecal Streptococci bacteria

FIG. 72

Conclusions

With regard to the objectives of this research as stated on page 1, the following are particularly important conclusions drawn from an analysis of the experimental data:

1. The volume source equations which describe the dispersion of any conservative constituent of a steady continuous waste plume can be extended to include the dispersion of a non-conservative waste material.

2. Using indicator bacteria as a particularly important non-conservative waste constituent, it was found that the derived growth-mortality patterns of both total coliform and fecal streptococcus group bacteria followed the mathematical model proposed by Streeter (1934). This equation is expressed in terms of three basic population parameters - two rate of reaction constants and what might be called an initial fictitious bacterial concentration.

3. In most of the experiments the derived growth-mortality patterns for both indicator groups did not follow the relationship commonly referred to as Chick's Law.

4. The population parameters characteristic of bacteria of the coliform group appeared to vary with such environmental factors as season of the year, water temperature, initial coliform concentration and the rate of subsequent dilution.

5. From the standpoint of engineering design analysis, water temperature and season of the year appear to be key environmental factors from which to estimate relevant values of coliform population parameters.

6. The population parameters pertaining to the fecal streptococcus group of bacteria exhibited little, if any, correlation with the environmental factors observed in these experiments.

7. On occasion, both indicator systems exhibited a tendency for the initial concentration to increase near the plume origin. In the case of the coliform bacteria, this tendency appeared to be related mainly to season of the year and water temperature. Initial growth of coliform organisms occurred duirng the winter and spring months when the water temperature was relatively low. Similar relationships for the observed growth patterns of fecal streptococci could not be established.

8. The phenomenon of aftergrowth of fecal streptococcus organisms in the downstream segment of a waste plume was observed in several experiments. The reason(s) for this phenomenon were not readily apparent. Aftergrowth of coliform bacteria did not occur in any of the field experiments.

9. The lateral and vertical distributions of mean tracer dye and coliform bacteria concentrations were found to be essentially saussian or normal. This result appears to justify the basic assumption of a normal concentration distribution inherent in the development of the mathematical models of oceanic dispersion as proposed herein.

10. The initial rate of subsequent dilution of a waste plume is strongly influenced by the size of the plume at the origin. A relatively smaller initial size will result in a significantly higher rate of initial subsequent dilution. This does not imply, however, that the ultimate dilution at a given point in the downstream segments of a surface plume will be greater for plumes of relatively smaller size. This is due to the fact that the lateral rate of diffusion, which contributes most significantly to the net dilution, is a function of initial plume size. The larger the initial width of a waste plume, the higher the lateral rate of diffusion. This result coupled with the fact that a larger initial plume width usually results in a higher initial dilution of the waste by the time it reaches the water surface, compensates for the relatively low initial rate of subsequent dilution observed in large-scale plumes.

11. An empirical relationship was established which relates the initial width of a waste plume to the length of diffuser section and surface current speed. Since the coefficient of lateral diffusivity as well as the initial dilution have been shown to be related to the initial width of a waste plume at the water surface, the derived relationship can be used in the design of submarine diffusers to produce optimum net dilution.

12. The continuity equation as applied to the physical conditions at the origin of a surface plume can be utilized to make reliable estimates of the initial depth of a plume.

Recommendations for Additional Research

These findings raise a number of questions that could perhaps be answered through further research. Some of the topics that merit fuller investigation are as follows:

1. The emperical equation relating the initial width of a surface plume and the lateral coefficient of eddy diffusivity should be extended to include a wider range of initial sizes or scales than observed in these experiments.
2. Although the equation of continuity can be used to estimate the initial depth of a surface plume, we do not know enough about the relevant environmental factors which influence this parameter. Additional experiments should be conducted to assess the effects of such factors as prevailing water column stability, waste discharge rate and length of diffuser section on initial depth.
3. Little experimental data is available from which to assess the signficance of differences in density on the lateral spread of waste plumes. Experiments should be conducted which are specifically designed to investigate the validity of recent theoretical concepts regarding this subject.
4. Full-scale field experiments should be conducted to investigate the growth-mortality characteristics of fecal coliform bacteria in the ocean. Within the past few years this indicator system has received wide acceptance as a

definitive indicator of fecal pollution.

5. Additional field experiments should be conducted on the growth-mortality patterns of total coliform and fecal stretococcus group bacteria as they occur in oceanic areas other than those described in this report.
6. With regard to the public health aspects of waste outfall design, it may prove interesting to conduct a series of experiments involving simultaneous measurements of growth-mortality patterns of enteric pathogenic bacteria and various bacterial indicator systems. With the advent of more sophisticated isolation techniques it appears that such experiments are now feasible. Such experiments may well answer the question as to which indicator system, if any, is the most definitive measure of fecal pollution in the ocean. As soon as suitable techniques are available these experiments should be extended to include enteric viral pathogens.

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